RISKS OUT OF DEPTH?

a study on the
environmental impacts
of seabed mining

LAURA KAIKKONEN

University of Helsinki 2021

Ecosystems and Environment Research Programme
Faculty of Biological and Environmental Sciences
Doctoral Programme in Interdisciplinary Environmental Sciences (DENVI)
University of Helsinki

RISKS OUT OF DEPTH? A STUDY ON THE ENVIRONMENTAL IMPACTS OF SEABED MINING

LAURA KAIKKONEN

ACADEMIC DISSERTATION

To be presented for public examination with the permission of the Faculty of Biological and Environmental Sciences of the University of Helsinki, in Auditorium PIII, Porthania (Yliopistonkatu 3), on the 29th of October 2021 at 13 o'clock.

Helsinki 2021

Supervised by: Docent Kirsi Kostamo
Biodiversity Centre
Finnish Environment Institute

Docent Laura Uusitalo
Programme for Environmental Information
Finnish Environment Institute

Professor Sakari Kuikka
Faculty of Biological and Environmental Sciences
University of Helsinki

Thesis advisory committee: Docent Joanna Norkko
Tvärminne Zoological Station
University of Helsinki

Docent Samuli Korpinen
Marine Research Centre
Finnish Environment Institute

Docent Samu Mäntyniemi
Natural Resource Institute Finland

Reviewed by: Dr. Sabine Gollner
Royal Netherlands Institute for Sea Research

Dr. Serena Hamilton
Australian National University

Opponent: Professor Anna Metaxas
Department of Oceanography
Dalhousie University, Canada

Custos: Professor Jukka Horppila
University of Helsinki

Author's address: laura.kaikkonen@iki.fi

ISBN 978-951-51-7535-9 (paperback)
ISBN 978-951-51-7536-6 (PDF)
http://ethesis.helsinki.fi

Cover art: Anni Kaikkonen
Articles I-IV are open access articles distributed
under the terms of Creative Commons CCBY 4.0 license

Painosalama, Turku 2021
Unigrafia, Helsinki 2021

To my grandparents, who loved the sea

SUMMARY

The oceans are facing increasing pressures from human activities. Growing industrialisation of the ocean space is giving room to both the expansion of existing and emergence of new ocean-based activities, with seabed mining one of the rapidly emerging sectors heralded as a solution to resource sufficiency. As ocean mining activities are still in exploratory stages, the development of seafloor mining is underpinned by high uncertainties on both the implementation of the activities and their consequences for the environment. Realising the full potential of the seas and oceans requires sustainable approaches to their economic development, mainly due to the issues related to the negative environmental effects, yet we lack tools and knowledge to comprehensively evaluate the impacts and further societal implications of emerging maritime sectors. To fill this gap, this thesis aims to provide a more detailed understanding of the environmental risks of seabed mining, factors affecting our understanding of those risks, and the knowledge requirements for evaluating emerging ocean industries.

This thesis consists of four papers and draws on an interdisciplinary approach that includes quantitative and qualitative analyses, modelling, literature reviews and knowledge syntheses. Paper **I** synthesises how the environmental impacts of seabed mining have been studied in the past and draws on parallel industries, such as aggregate extraction, to increase the knowledge of the impacts on marine ecosystems. It underlines that most studies have assessed the impacts narrowly, with little appreciation of the uncertainties or cumulative effects. In this paper, I further reflect on areas that need development for comprehensive environmental risk assessments for seabed mining. Paper **II** contributes to the baseline information on marine mineral precipitates, estimating the distribution of ferromanganese (FeMn) concretions using spatial modelling techniques. In paper **III**, I develop a probabilistic modelling framework for assessing the risks of seabed mining. Drawing on information collected in paper I, this study outlines the cause-effect pathways related to seabed mining activities through a series of interviews with a multidisciplinary group of experts. The risk model is then used to illustrate the impacts of FeMn concretion extraction on benthic fauna in the Baltic Sea, offering a quantitative means to highlight the many uncertainties around the impacts of mining. Paper **IV** examines whether people care about the impacts of human activities in remote locations. In this paper, I evaluate the dimensions of environmental care for the deep sea and relate this to the perceived risks of seafloor mining by comparing the deep sea to three other remote environments: Antarctica, the Moon, and remote terrestrial environments. The results of this work show that despite people's low knowledge of the deep sea, people do care about mining activities harming deep-sea ecosystems, and that a stronger emotional connection to remote environments is positively connected to environmental care and perception of the severity of the risks of mining.

This thesis contributes to a more comprehensive understanding of the environmental risks of seabed mining and advocates a more transparent approach to emerging industries and their risks. The combined findings of this work suggest that it is fundamental to both increase knowledge of the environment that will be affected by the risks, and to account for the underlying values and emotions towards the marine environment to fathom how those risk will be perceived. An improved appreciation of the risks of emerging maritime industries will be essential to avoid uncontrolled developments and to ensure good stewardship of the marine environment.

Keywords: blue growth, causal networks, environmental risks, marine minerals, stewardship

CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following publications:

I. Kaikkonen, L., Venesjärvi, R., Nygård, H., & Kuikka, S. 2018. Assessing the impacts of seabed mineral extraction in the deep sea and coastal marine environments: Current methods and recommendations for environmental risk assessment. *Marine pollution bulletin*, *135*, 1183-1197.

II. Kaikkonen*, L., Virtanen*, E. A., Kostamo, K., Lappalainen, J., & Kotilainen, A. T. 2019. Extensive coverage of marine mineral concretions revealed in shallow shelf sea areas. *Frontiers in Marine Science, 6, 541.*

*These authors contributed equally to this work.

III. Kaikkonen, L., Helle, I., Kostamo, K., Kuikka, S., Nygård, H., Törnroos, A., Venesjärvi, R., Uusitalo, L. 2021. Causal approach to determining the environmental risks of seabed mining. *Environmental Science and Technology, 55 (13), 8502-8513.*

IV. Kaikkonen, L., van Putten, I. 2021. We may not know much about the deep sea, but do we care about mining it? *People and Nature, 3: 843– 860.*

The publications are referred to in the text by their roman numerals.

AUTHOR CONTRIBUTIONS

I: LK, RV, and SK had the original idea for the study. LK framed the review questions and reviewed the literature. LK wrote the review with input from RV, SK and HN.

II: LK, EV, AK, and KK designed the study. LK was responsible for the literature on variables and parameter selection. EV performed all the analyses with the help from LK. LK and EV jointly analysed the results, wrote the main text, and prepared the figures. All authors contributed to the editing manuscript.

III: LK, RV and SK had the original idea for the study. LK designed and carried out the expert elicitation with supervision from IH, KK and LU. LK analysed the results, built the model, and wrote the manuscript. All authors contributed to the editing of the manuscript.

IV: LK and IvP designed the study. LK was responsible for the data analysis, performed the statistical tests, and produced the figures. LK and IvP analysed the results and wrote the manuscript jointly.

LK: Laura Kaikkonen, EV: Elina Virtanen, AK: Aarno Kotilainen, KK: Kirsi Kostamo, SK: Sakari Kuikka, HN: Henrik Nygård, LU: Laura Uusitalo,
RV: Riikka Venesjärvi, IvP: Ingrid van Putten

ABBREVIATIONS

BN: Bayesian Network

CPT: Conditional probability table

DAG: Directed acyclic graph

EBM: Ecosystem-based management

EIA: Environmental impact assessment

ERA: Environmental risk assessment

REE: Rare earth element

SBM: Seabed mining

1 INTRODUCTION

Economic development and human activities in the ocean are accelerating rapidly, introducing seas and oceans to a new phase of large-scale industrialisation (Barbesgaard 2018; Jouffray et al. 2020). Old and new maritime activities are the subject of many government, research, and industry initiatives to expand the Blue Economy, a term which has come to encompass a range of activities and policies which, if carefully managed and coordinated, could secure socio-economically and environmentally sustainable ocean resource use (Voyer et al. 2018; Lee et al. 2020).

Uncertainty regarding the environmental impacts associated with the expansion of maritime activities is a key concern impeding the sustainable Blue Economy. Public perceptions of the combined environmental and societal risks from developing maritime industries can significantly influence the political and regulatory processes that underpin these activities (Gelcich et al. 2014; Lotze et al. 2018) and affect their future development (Voyer and van Leeuwen, 2019). Failing to broadly consider the environmental risks of maritime developments can thus lead to unbridled expansion of maritime sectors with negative consequences for both the marine environment and society (Bennett et al. 2019). As we lack the required tools and knowledge to comprehensively evaluate the impacts of activities that do not take place yet, it is essential to better understand the risks of emerging industries and how they are viewed to avoid uncontrolled developments and to ensure good stewardship of the marine environment. This thesis is a study of the environmental risks associated with emerging ocean industries through the lens of seabed mining, focused on the knowledge requirements for evaluating environmental risks and whether we as societies care about them.

1.1 BLUE GROWTH INITIATIVES INCREASE HUMAN IMPACT ON MARINE ECOSYSTEMS

The human expansion into the ocean is embodied both through the expansion of existing activities (Halpern et al. 2015) and the emergence of completely new industries for marine resource use (Voyer et al. 2018, Winther et al. 2020). With an already crowded coastal zone, an increasing number of maritime activities are moving offshore (Novaglio et al. 2021). Technological advances and lower extraction costs now enable exploitation of previously inaccessible marine resources, including those in the deep sea, which is promoted as a new frontier for resources and exploration (Ramirez-Llodra et al. 2011; Harden-Davies 2017).

The industrialisation of the oceans introduces additional environmental impacts on an already overburdened marine environment (Nash et al. 2017). Despite efforts to balance use and conservation, the past decades have seen over-exploitation of ocean resources (Halpern et al. 2008; Duarte and Krause-Jensen 2020), and the existing policies have not been successful in halting the biodiversity loss and environmental degradation in the world's oceans (e.g. Boyes et al. 2016). Cumulative effects of multiple sectors together with climate change, over-exploitation of resources, and pollution further add to the pressures on marine environments with uncertain consequences (Halpern et al. 2019). At the same time, we increasingly recognise the multiple benefits to human wellbeing from the oceans (Halpern et al. 2012; Fleming et al. 2019). The Blue Economy thus finds itself at the intersection of high expectations of increasing economic benefits, and the marine environment in need of protection (Eikeset et al. 2018; Voyer et al. 2018).

Against the backdrop of this recognition, sustainability has grown as a guiding principle to ensure socio-economic development that does not lead to significant degradation of the environment or to societal inequity (UNESCO 2019). As a result, a number of approaches have emerged in recent decades to support sustainability in the marine realm (Stephenson et al. 2021). In particular, the concept of ecosystem approach or ecosystem-based management (EBM) is promoted as the overarching principle in environmental management. A core tenet of EBM is that humans are seen as an integral part of a coupled social-ecological system (SES) which should be accounted for in environmental management (Levin et al. 2009; Long et al. 2015).

Despite the rise of sustainability and EBM as overarching concepts for natural resource governance, there is still a divide between the aims to protect the marine environment while at the same time facilitating its exploitation (Portman 2016). This discrepancy is particularly due to divergent views of the environmental impacts of human activities and their subsequent effects on societies (Voyer and van Leeuwen 2019). Realising the full potential of the seas and oceans thus requires to err on the side of caution and promotes the need to predict the environmental consequences of new industries on the marine ecosystem and human society (Wang 2011; Wright 2015).

However, tools and processes to understand and manage the environmental risks of novel maritime activities are still largely underdeveloped or often do not exist (Bennett et al. 2019). The recognition of the complex interactions within societies and the marine environment to achieve sustainable Blue Economy calls for the application of more holistic approaches and systems-level thinking to these challenges (Hodgson et al. 2019). The impacts of new activities should thus be carefully evaluated prior to permitting them to enable broader evaluation of their net benefits of to society.

1.2 SEABED MINING

Mining the ocean floor for mineral resources is one of the rapidly developing sectors embodying many of the expectations of the Blue Economy, particularly by releasing pressure from land-based ecosystems and the envisioned profitability of extraction (Hein et al. 2013; Batker and Schmidt 2015; Van Nijen et al. 2018). Coastal resources, such as sand and gravel, have been extracted from the shallow seabed for decades, fuelled by increasing global demand from the construction industry (Peduzzi 2014; Hannington et al. 2017).

A similar development is driving the interest in metals from the seabed. Global infrastructure development and transition to low-carbon technologies are increasing the demand for transition metals and rare earth elements (REEs) (Nansai et al. 2014; Vidal et al. 2017). Cobalt, lithium, and nickel are branded as the world's primary technology metals to be used e.g. in ion batteries, and many REEs are seeing new applications in electronic components and industrial processes. The rising demands of these elements, whose consumption could exceed current production rates in the coming decades (Elshkaki et al. 2016), are driving the interest in extracting these minerals from the seafloor.

Framed as a more sustainable alternative in light of the high environmental and societal impacts of terrestrial mining (Sonter et al. 2020), seabed mining (SBM) is heralded as an integral part of the Blue Economy[1] and as a means to meet resource demand (Childs 2019). The higher concentration of transition metals and REEs in seabed deposits compared to land-based ores further contributes to their resource potential and appeal for mining operations (Petersen et al. 2016). Although the economic potential of seabed minerals has been recognised for decades (Mero 1965), the technological constraints and political uncertainty, particularly in international waters, have made industrial mining unfeasible (Zalik 2015). While most initiatives are still at an exploratory stage and extensive commercial mining projects have not been initiated, the increasing need for raw materials is pushing countries to consider where to get their mineral resources in the future (Vidal et al. 2017).

Extraction of minerals from the seabed covers a range of mineral ore types found in both shallow water and the deep sea (below 200 m). Mining activities are targeted at different kinds of mineral ores and deposits but the term SBM primarily refers to polymetallic nodules, seafloor massive sulphides, and cobalt-rich crusts (Peukert et al. 2018), found both within and outside national

[1] Depending on the definition, SBM may or may not be included in the Blue Economy, as sustainability of non-renewable resources is inherently debated problematic (Kuhlman and Farrington 2010; Voyer et al. 2018). Despite this ongoing debate, in this thesis I consider SBM as one of the offshore sectors included in the developing Blue Economy, without entering into the definitions of sustainable extraction of minerals.

waters and exclusive economic zones (EEZ). It is thus important to note that SBM does not refer to a single phenomenon (Carver et al. 2020), but a range of activities under different environmental and regulatory contexts, spanning from the deep sea to shallow water environments, and from international waters to activities under the jurisdiction of sovereign states.

In 2017, the Japan Oil, Gas, and Metals National Corporation completed the world's first deep-sea mining trial in Japanese waters (JOGMEC 2018). In the deep sea beyond national jurisdiction, more than 1.3 million km^2 of the seabed have been licensed for exploratory mining licenses, with exploitation regulations expected to be approved in the coming years (ISA 2018; Miller et al. 2018). While much of the research pertaining to SBM concerns mining of the deep seabed, the high cost and technological challenges of operating in the deep sea are driving further interest in mineral extraction from shelf seas (Hannington et al. 2017). In 2006–2008, commercial extraction of ferromanganese deposits was briefly carried out in the Russian part of the Gulf of Finland using hydraulic dredging (Zhamoida et al. 2017). With the rising resource demand and prices, further commercial mining in the Baltic Sea and other coastal areas may be considered in the near future.

SEAFLOOR MINERAL DEPOSITS

Mineral precipitates, including polymetallic nodules and other mineral concretions, are one of the most sought after seabed resources deemed to hold the greatest economic promise (Hein et al. 2013). Mineral concretions form at the interface of the sediment surface and water through a combination of biogeochemical processes and contain high concentrations of iron, manganese, phosphorus, copper, cobalt, and REEs (Baturin and Dubinchuk 2009; Yli-Hemminki et al. 2014; Kuhn et al. 2017). Concretions are widespread in the world's oceans, occurring e.g. in the Black Sea (Baturin 2010), north-east Atlantic Ocean (González et al. 2010), South China Sea (Zhong et al. 2017), and Kara Sea (Vereshchagin et al. 2019). Despite their widespread occurrence in shallow-water environments, considerably more research has been carried out on deep-sea nodules (Kuhn et al. 2017).

Of the shallow water environments where mineral concretions are observed, ferromanganese (FeMn) concretions (Fig. 1) in the northern Baltic Sea have been deemed particularly abundant (Winterhalter 1966; Boström et al. 1982). In high numbers, they form a distinct underwater habitat type (HELCOM 2013). While the processes affecting concretion formation have been studied from a geological perspective for decades (Ingri 1985; Baturin 2010; González et al. 2010), FeMn concretion fields in the Baltic Sea are classified as a data deficient habitat type (Kotilainen et al. 2018), with no collated information on their abundance, spatial coverage, or other characteristics. As three dimensional structures on otherwise soft seafloors, concretions potentially form an important habitat for marine organisms and contribute to other ecosystem functions, such as retention of nutrients and heavy metals (Veillette et al. 2007; Reunamo et al. 2017). It is therefore surprising how little attention these mineral deposits have gained thus far from a non-geological perspective. In anticipating future acquisition of new resources, it is necessary to know where (and when) that exploitation might occur.

Figure 1. Discoidal ferromanganese (FeMn) concretions and a seafloor covered by FeMn concretions (Images: L. Kaikkonen; SYKE).

IMPACTS OF SEABED MINING ON THE MARINE ENVIRONMENT

While improved geological methods have enabled high-resolution mapping of new seafloor mineral reserves and advanced technologies enable their exploitation, the environmental impacts of seabed mining are still poorly understood. In the deep sea, the environmental impacts of SBM have been addressed in a number of experimental studies, which have consisted of simulating the effects of polymetallic nodule extraction using a mechanical seabed plougher (e.g. Thiel et al. 2001; Jones et al. 2017; Orcutt et al. 2018). Coupled with modelling approaches, these studies have offered valuable insights into the potential impacts of mining, and indicate extremely slow recovery times of the seabed habitat both in terms of biological communities and sediment geochemistry (Khripounoff et al. 2006; Miljutin et al. 2011; Gollner et al. 2017; Simon-Lledó et al. 2019). Even with the valuable data from these experiments, it is uncertain to what extent the empirical disturbance studies succeed in scaling up to industrial mining operations both in space and in time (Jones et al., 2017).

In coastal sea areas, several studies have been conducted as a result of decades of extensive aggregate extraction (e.g. Newell et al. 1998; Newell et al. 2004). While exploratory extraction of FeMn concretions was carried out in the Baltic Sea in 2006–2008 (Zhamoida et al. 2017), no biological monitoring data of this trial have been made available. The impact studies conducted to date thus offer only a scattered view of the environmental impacts of SBM, with no attempts to synthesise impacts that would support an operational assessment. This lack of previous evidence to draw on requires a different view on how we assess impacts of human activities.

1.3 ENVIRONMENTAL RISKS

Environmental impact assessment (EIA, (Munn 1979; Glasson et al. 2013) is a key tool in planning and evaluating the effects of human activities on the environment, and as such serves as an integral component of licensing operations. Direct obligations under both international law and national jurisdictions require conducting prior EIA for projects that are likely to have significant adverse effects on the environment (Pérez 2017). However, in their current use, EIAs are criticised for not providing an adequate overview of the different outcomes of an activity, with often insufficient justification on statements on the severity of the impacts (Drayson et al. 2015; Guerra et al. 2015).

Environmental risk assessment (ERA) is a process of estimating the probability and magnitude of the effects of human activities on the environment (Jardine et al. 2003; Burgman 2005). While not a statutory requirement, ERA are increasingly included in EIA to account for the uncertainties related to environmental impacts (Suter II 2016) and to guide management actions (Ascough Ii et al. 2008). A comprehensive ERA, therefore, fills in some of the gaps in traditional EIA processes by accounting for the unlikely scenarios and highlighting where information is needed. As the paucity of previous evidence from marine mineral extraction limits the implementation of traditional EIA (Clark et al. 2019), ERAs can play a significant role in dealing with uncertainty as a part of the impact assessment.

Moving from an impact assessment to a risk assessment involves adding a probabilistic element, with a risk in this context defined as the likelihood of an event in addition to its severity (Burgman 2005). Following this probabilistic view of risk, a risk is characterised not by a single event but by a set of possible events or outcomes and their respective probabilities (Fenton and Neil 2012).

The uncertainties underpinning SBM, both in terms of baseline data and knowledge of its impacts, pose a challenge of how to estimate the risks in a way that is both ecologically solid, and robust in a decision-making and policy context (Folkersen et al. 2019; Ginzky et al. 2020; Kung et al. 2020). Even with ample empirical data, it is impossible to estimate the probability and magnitude of an event with absolute certainty (Hansson 2009). In addition, most ERAs build on estimating ecosystem responses to pressures based on vulnerability of the environment through semi-quantitative scoring instead of focusing of the activity itself (Stelzenmueller et al. 2015; Washburn et al. 2019; Quemmerais-Amice et al. 2020), and as such are not well suited for describing different possible combinations of outcomes from new untested activities.

While ecological unknowns are deemed to impede the application of quantitative ERAs especially within the deep-sea mining context (Washburn et al. 2019), quantitative risk assessments can highlight the uncertainties around the key sources of risk (Hart and Pollino 2008). To adequately estimate the impacts of SBM, it is essential to develop methods to comprehensively predict the associated ecosystem responses and to account for the uncertainties embedded in these estimates.

An improved appreciation of risks to both the ecosystem and societies forms a key step toward operationalising EBM to assess if activities are likely to cause unacceptable effects on the marine environment. This further supports a precautionary approach as part of EBM, as outlining the level of "serious harm" is used as the key trigger for preventive and precautionary measures (deFur and Kaszuba 2002; Peel 2005; Long et al. 2015). As commercial mining activities have not started yet, this provides a unique opportunity to assess what the impacts to marine ecosystems will be, and to consider whether it is economically profitable to exploit seabed mineral resources with respect to the environmental impacts and the subsequent societal and economic costs (Levin et al. 2020; Haugan et al. 2020). The question thus becomes whether–and to what extent–predictive risk assessments can support decision making for sustainable resource governance?

1.4 ROLE OF ENVIRONMENTAL VALUES IN MARINE RESOURCE GOVERNANCE

Governing the risks of human activities extends beyond the simple evaluation of the risk of an event (Aven and Renn 2010; Wachinger et al. 2013). While technical risk assessments are elemental in evaluating impacts of novel activities, making decisions on the outcomes of those assessment relies on how the impacts are perceived (Gregory et al. 2006; Parviainen et al. 2019). In order to care about adverse impacts to an environment, we must both think there is a risk to be concerned about, and care about what is at risk.

A longstanding scholarship on risk perceptions evaluates people's judgements regarding the nature of hazardous events, including their probability and severity of consequences (e.g. Starr 1969; Kasperson et al. 1988; Gustafsod 1998; Sjöberg 2000; Bickerstaff 2004). Knowledge of the sources of risks and what is at risk has been shown to impact both the emotional and cognitive dimensions of risk perceptions (Tversky and Kahneman 1979; Slovic et al. 2004; Slovic and Slovic 2013; Sobkow et al. 2016). These differing individual and social perceptions of risk have long been recognised as an essential component of decision making (Tversky and Kahneman 1979; Renn 1998). After decades of focus on the cognitive aspects of risk, the way people feel about a particular risk is now deemed to have a more significant impact on their perception of it than how well they are informed about it (Loewenstein et al. 2001; Slovic et al. 2004). Similarly, while it is unlikely for people to care about an environment they know nothing about (Clayton and Myers 2015), people's emotional connection to nature is suggested to be more important in contributing to environmental care than literacy (Stern and Dietz 1994; Leiserowitz 2006; Sobkow et al. 2016; Lumber et al. 2017).

Values are one way to measure people's emotional connection to nature and to examine how much people care about a certain environment (Perkins 2010; Klain et al. 2017). The current discourse recognises a variety of values that may be attributed to an environment, ranging from intrinsic and instrumental values to relational values (Chan et al. 2016; Pascual et al. 2017; Tadaki et al. 2017), unravelling what different environments mean to people (O'Neill et al. 2008). Most studies on how we value seas and oceans have focused on the valuation of goods and other instrumental values from the marine environment (Armstrong et al. 2012; Aanesen et al. 2015; Sagebiel et al. 2016). In turn, the non-use values, symbolic meanings, and emotions associated with the oceans have been little explored (Šunde 2008; Kearns and Collins 2012; Gee 2019).

One aspect impeding broader ocean valuation studies is that most current approaches examining people's values for the environment posit that values are informed by experiential and rational ways of relating to environments (e.g. "I value this environment *because* I enjoy the things it provides") (Brown and Reed 2000; Tadaki et al. 2017). As such, these approaches are not well suited for studying values and perceptions of remote and unfamiliar environments, such as the deep seafloor and other offshore environments. In this thesis, I conceptualise the underlying values attributed to an environment through the notion of symbolic values, that is, the emotions and meanings the environment represents, relevant not primarily to itself, but how we view and value it (Bruner and Postman 1948). In the context of SBM, I hypothesise that these values can shed light on whether people care about marine environments that will be affected by mining activities.

The reason we should care about care is that the way we perceive and value the environment affects how we treat it. Caring about nature constitutes a key dimension of environmental stewardship, contributing to responsible management of the environment (Bennett et al. 2018; Mathevet et al. 2018). Caring or not caring about the marine environment and its state thus links to whether we will take action to protect it or not and may act as a filter to how environmental risks are perceived (Clayton 2003; Jones et al. 2016; Enqvist et al. 2018; Jax et al. 2018; West et al. 2018).

Perceptions of emerging maritime activities and the risks they pose to the environment (Gelcich et al. 2014; Lotze et al. 2018) can further influence the political and regulatory processes that underpin the development of these activities (Wachinger et al. 2013). Although the risks of offshore activities have most often been approached through environmental impacts, there are many economic and societal considerations to be accounted for (Hansen et al. 2016; Wilson and Stammler 2016; Bennett et al. 2021). The combined appreciation of the environmental and societal risks affects public perceptions of them and further contributes to the societal acceptance of maritime developments which is likely to guide their future development (Mason et al. 2010; Voyer and van Leeuwen 2019). In turn, negligence about the risks can lead to unbridled ocean development with considerable negative consequences for both the marine environment and society (Bennett et al. 2019).

1.5 AIMS AND SCOPE OF THE THESIS

The overarching aim of this thesis is to study the environmental risks of emerging maritime industries, using seabed mining as a case study (Fig. 2). I particularly focus on the knowledge prerequisites for assessing these risks and how to synthesise this information. I am also interested in what role underlying values and emotions play in risk perceptions and care towards human activities in unfamiliar environments, such as the deep seafloor. The thesis includes four papers, spanning from a regional focus on the Baltic Sea (papers **II&III)** to a more global view (papers **I&IV**) and from shallow water (paper **II**) to deep sea (paper **IV**).

Paper **I** synthesises the available information on the impacts of seabed mineral extraction and examines how the risks have been studied. Paper **II** provides information on the distribution of the seabed mineral concretions in the Baltic Sea using spatial modelling techniques. Paper **III** draws on expert interviews and the findings of paper **I** to provide a causal approach to the ecological impacts of extracting FeMn concretions in the Baltic Sea using probabilistic modelling. Finally, paper **IV** examines the risks of seabed mining through people's care for mining in the deep sea and relates this to the symbolic value people place on remote environments.

The work addresses the following questions:

1) What are the knowledge gaps in understanding the impacts of seabed mining? (papers **I&II**)
2) How can predictive risk assessments for novel offshore activities be developed? (paper **III**)
3) What role do underlying values and emotions play in risk perceptions and care towards human activities in remote environments? (paper **IV**)

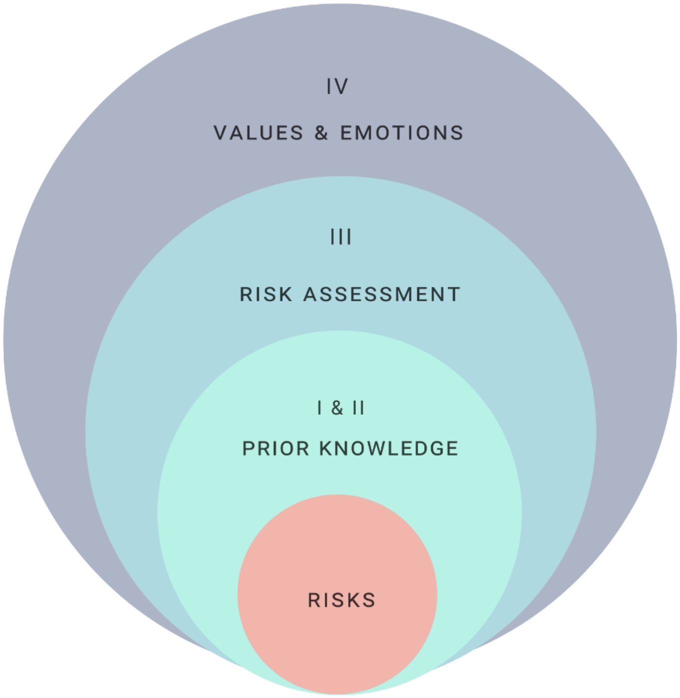


Figure 2. Factors contributing to improving views of environmental risks of emerging maritime activities considered in this thesis.

2 MATERIALS AND METHODS

This thesis uses both qualitative and quantitative approaches to answer the research questions outlined above. Working with impacts of activities that do not occur yet calls for an integration of information from multiple sources, and as a result, the papers differ in their scales of analysis and array of methods used. Importantly, I recognise the importance of accounting for multiple sources of knowledge and using available information in addition to scoping new knowledge and data (Table 1).

Table 1. Overview of the sources of information and methods used in the thesis.

Paper	Research question	Sources of information	Methods	References
I	What prior information is available on impacts of seabed mining?	Peer-reviewed literature	Literature review	Section **2.1.1**
II	Where are mineral concretions located?	Underwater inventory (VELMU) data, literature	Boosted regression trees	Sections **2.1.1** and **2.2**
III	How can ecological impacts of seabed mining be quantified?	Expert elicitation, literature	Expert informed Bayesian networks	Sections **2.1.2** and **2.3.1**
IV	What contributes to people's care about remote environments, such as the deep seabed?	Online survey	Algorithm based Bayesian networks	Sections **2.1.3** and **2.3.2**

2.1 SOURCES OF INFORMATION AND METHODOLOGICAL APPROACHES

2.1.1 EXISTING KNOWLEDGE AND DATA

Paper **I** serves as a foundation for evaluating the impacts of extracting minerals from the seabed. The work presents a synthesis of empirical evidence from experimental SBM and aggregate extraction studies and parallel industries to infer the effects of seabed mineral extraction on marine ecosystems. I conducted a literature review with studies on the impacts of deep-sea mining and aggregate extraction as a starting point, and then expanded the search to the specific pressures mentioned in those studies. To gain a systematic understanding of the linkages between the activity and the affected ecosystem components, paper **I** uses a problem-structuring framework to evaluate causal relationships between the physicochemical pressures from mineral extraction and the potential changes in marine ecosystems.

In paper **II,** we used an extensive dataset of nearly 140,000 observations from underwater inventories by the Finnish Marine Underwater Inventory Programme VELMU. These data cover the whole coast of Finland, where each location has been surveyed either through scuba-diving or a drop-camera. The data include information on both biological and geological seabed features, including FeMn concretions, where concretions have been recorded either as being present (with certain percentage coverage) or absent. Each site has been visually analysed by a trained technician or by a scientific diver.

Based on these data, a number of predictor variables were developed for predictive modelling (II, Virtanen et al. 2019). We used these predictors and the VELMU data to develop predictive models for FeMn concretion distribution and abundance. Additional data on the environmental predictors used in this study were derived from the Finnish national environmental monitoring database Hertta and the public bathymetry databases of the Finnish Transport Infrastructure Agency (Väylä).

2.1.2 EXPERT KNOWLEDGE

Drawing on the outcomes of the literature review in paper **I**, paper **III** relied on expert knowledge to further detail the factors involved in the ecological risks of FeMn concretion extraction. Expert knowledge was first collected in semi-structured interviews to map the cause-effect pathways between pressures from mining and the affected ecosystem components, and at a later stage through probability elicitation to quantify the magnitude of the ecosystem responses.

I contacted experts via snowball sampling by consulting researchers in different fields of marine sciences. In addition to selecting experts based on their substance expertise and recognised merits, I was interested in interviewing people with varying backgrounds from different institutes who would support obtaining a comprehensive view of the ecosystem. Interviews were carried out gradually to evaluate when a sufficient number of experts had been interviewed by monitoring when the addition of new experts no longer introduced new information. For this study, I interviewed 11 experts from universities in Finland and Sweden, governmental research institutes, as well as intergovernmental organizations working on the Baltic Sea.

Framing the system and the connections between variables during the interviews was performed as a causal mapping exercise. The aim of causal mapping is to explore an individual's view on a system or a presented scenario by detailing the causes and effects within the studied system. At the beginning of each interview, experts were presented with the same scenario of how and where mining would take place. The case study in this paper deals with FeMn concretions extraction in the northern Baltic Sea (Gulf of Finland – Archipelago Sea region) in depths below 40 meters. Details on how the mining would likely happen were drawn from both literature and consultation with experts in mining technology.

The physicochemical pressures identified in paper **I** served as a starting point for the mapping exercise and interviews. Experts were then asked which ecosystem components they thought would be affected by these pressures. When possible, I requested experts to rank the strength of the connection on a scale from one to three. For the biological variables, evaluation was based on functional groups of organisms instead of species. After interviews, causal maps were digitised and sent to the experts for verification and any further comments and additions.

I combined the results from the individual causal maps into one network to obtain a comprehensive view of the environmental impacts of mining and factors related to them. To do this, I coded the connections between variables in the individual causal maps to adjacency matrices using the assigned link strengths whenever available. Prior to combining the maps, variables were harmonised and combined so that similar concepts were grouped under one variable. To ensure that the combined map and the harmonised variables still represented the views of the individual experts, details on the model structure were made available in an open online document that presented the model both in the form of a graph and a table detailing the rationale for the causal connections. At a later stage, expert knowledge was used to formalise the quantitative probability estimates used in the probabilistic risk model (see section 2.2. below).

2.1.3 SURVEY DATA

In paper **IV**, we developed an online survey to collect information on how people value different remote environments and how that affects their care about mining activities in those environments. We particularly explore the role of symbolic values, which we define as the emotions, moods, and meanings an environment evokes, as an element affecting people's care for the environment (Bruner and Postman 1948). To gain a broader view on the role of remoteness on whether people care about an environment, we compare the deep sea to three other environments: Antarctica, remote terrestrial environments, and the Moon.

To examine the underlying values and emotions people hold for remote environments, we constructed a symbolic value typology based on previously established typologies for environmental values (Brown and Reed 2000; Kellert 1993; Brown and Raymond 2007; Kellert 1997) and previous studies on ocean perceptions (e.g. Jefferson et al. 2015) and named antonyms for these words. This resulted in eight positive and negative symbolic values to measure affective response for the deep sea and the three other environments.

To measure environmental care, we asked survey respondents how much they would care about something bad happening to the environment in question. In addition to environmental care, we investigated the respondent's knowledge, worldviews, and the perceived environmental and societal risk of mining. The reason for differentiating between environmental and societal risk was that we did not want to assume that perception of the overall risk of an activity would be only dictated by the expected environmental damage, and that societal riskiness of an activity may stem from economic risks, risk to human safety, environmental degradation, or other reasons. We further asked whether people believed it likely that mining would occur in these environments in the near future. Broad values were evaluated through an environmental portrait-value-questionnaire (Bouman et al. 2018) based on Schwartz's value typology (Schwartz 1992; Schwartz 1994) and New Ecological Paradigm (NEP) as a measure of general pro-environmental beliefs (Dunlap and Van Liere 1978; Dunlap et al. 2000).

The final survey contained 27 questions on the aspects that to our mind contribute to environmental care: symbolic values, environmental and societal perceptions of risk of mining, knowledge of the environment and human activities, the perceived likelihood of mining in the future, broad values and worldviews, and demographics. The survey was distributed online to a volunteered public through social media and email lists and was administered using the open-source platform Limesurvey.

2.2 BOOSTED REGRESSION TREES

In paper **II**, we used Boosted Regression Trees (BRT) to generalise the relationship between FeMn concretion occurrence and abundance to the environmental conditions in which they are found (Friedman et al. 2000; Breiman 2017). BRTs are an ensemble modelling method for fitting statistical models that combine regression trees and boosting. As an addition to regular regression trees, the use of boosting, an adaptive method for sequential combination of multiple simple models, increases the predictive performance of the models (De'Ath 2007).

Environmental parameters were chosen based on previous studies on concretion occurrence, formation, and biogeochemistry. For modelling the distribution and abundance of concretions, we utilised existing environmental predictors characterising seascape topography and other qualities (Virtanen et al. 2018; Virtanen et al. 2019) and further developed spatial predictor variables thought to be relevant for FeMn concretions (e.g. bottom water phosphorus concentration).

Concretion occurrences were modelled with thresholds based on four different coverages on the seafloor: >0.1 % (presence/absence information only), >10 % (abundant concretions), >50 % (substantial cover) and >70 % (concretion fields). Concretion abundance was modelled as a continuous response variable (0–100 %), utilising all available data on the reported coverages. The reason for these different variables is that we assumed the percentage coverages, especially at low coverages not to be equally reliable, as detection of concretions on the seafloor may be impeded by water turbidity or sedimentation. Detection accuracy further depends on the observation method, SCUBA diving being a more reliable method than the video, which is skewed towards higher coverages.

To keep modelling times reasonable, only a fraction of the available ~140,000 visited locations were used to produce the models. We used 20,000 of the field samples and split the dataset with a ratio of 40:60 for model training and testing the model performance. The best models from the cross-validation were extrapolated to the full seascape at a 20 m resolution to produce maps predicting the concretion distribution and abundances using the testing data withheld from model building.

2.3 BAYESIAN NETWORKS

Bayesian networks (BN) are probabilistic models that represent a joint probability distribution over a set of variables (Pearl 1988). A BN is comprised of 1) a directed acyclic graph (DAG) describing the conditional dependencies between variables and 2) the strength of these dependencies quantified by conditional probabilities (Pearl 1986; Lauritzen and Spiegelhalter 1988).

As BNs handle the connections between variables (or nodes) based on probabilities instead of simple scores, uncertainty is explicitly accounted for. The result of a BN is therefore not a single outcome, but a distribution over the possible values of each variable, which allows estimating not only the most likely outcome, but also the uncertainty associated with the estimates (Nielsen and Jensen 2009; Fenton and Neil 2012). Using the Bayes rule, BNs allow computing posterior probabilities of an event given new evidence, enabling to evaluate alternative scenarios and their probabilities. They also allow for backward calculus from effects to causes, which may be used in diagnostic analysis.

Both the structure and the parameters (conditional probabilities) of a BN can be defined either by using algorithms to infer them from data or through expert judgment drawing on previous studies, data, and literature. When defined manually, the structure of a BN usually depicts the known or perceived causal relationships in the modelled system. This qualitative causal representation alone can help understand the sources of risks and inform potential management actions to control those risks (Chen and Pollino 2012; Carriger et al. 2018). Structural learning refers to learning the DAG from data, using a number of different possible algorithms (Barber 2012). For evaluating the conditional probabilities, BNs may be used to integrate different kinds of knowledge, from expert opinion to data, making them well-suited for cases where little or scattered information is available. Estimating parameters of a BN from data is a very data-heavy exercise, ideally requiring data on all the different combinations of the variable states.

In an environmental risk assessment context, BNs can be used as a scenario synthesis tool, in which all possible combinations of events are taken into account by considering the probability of their occurrence (Varis et al. 1990; Fenton and Neil 2012; Carriger et al. 2016). Due to their modular structure, individual BNs may be interlinked to form a more holistic system and to integrate outcomes from separate studies and sub-models to support iterative updating of the model as new information becomes available.

In this thesis, BNs are used for two purposes: for synthesising knowledge on the structure of the marine ecosystem under the pressures from mining through an expert-defined network and the conditional probabilities describing the connection between variables (paper **III**), and for evaluating the dependencies between variables in the survey data to find the most significant connections in the dataset (paper **IV**). All BN analyses are done using the *bnlearn* (Scutari 2009) package for R.

2.3.1 EXPERT-DEFINED MODEL STRUCTURE

In paper **III,** the causal models developed with experts were used to build a risk model to estimate the effects of seabed mining on the Baltic Sea ecosystem. The BN serves as a modelling framework to synthesise knowledge of the studied system and to accommodate information from different sources.

We quantified a sub-model of the complete causal network developed in the first part of the study (see 2.1.2 fordetails) focusing on three groups of benthic fauna. The BN model (Fig. 3) was developed from a subset of the larger causal network and included variables describing these benthic faunal groups, the main pressures affecting them, and any intermediate variables. We restricted the model to account only for the acute impacts within a spatially discrete mining block (area) to reduce model complexity. Variable states were drawn from literature and expert opinion.

Direct and indirect mortality were modelled separately, so that the total mortality of benthic fauna comprises both the direct mortality from the extraction of sediment and mineral concretions and the indirect mortality stemming from the other pressures from the extraction activity. This allows for estimating the effects of the pressures for both the direct mining area (total mortality) and in neighbouring areas (indirect mortality). The conditionally independent variables in the network may be used to evaluate alternative mining scenarios.

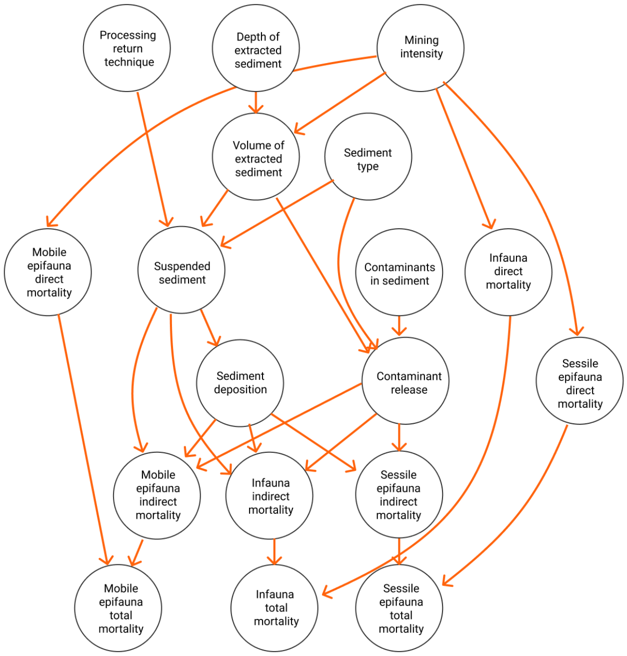


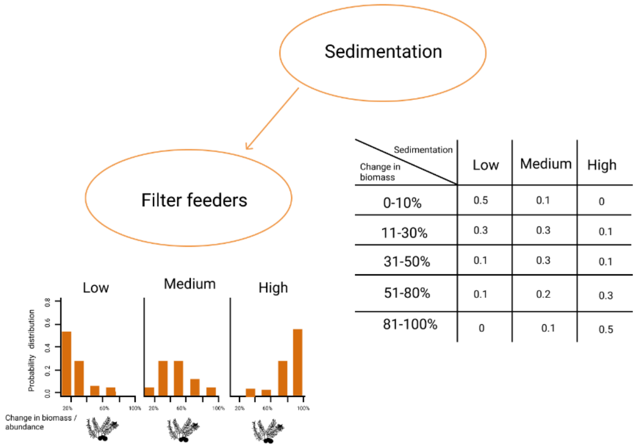
Figure 3. Bayesian network for impacts of seabed mining on benthic fauna developed in paper III. Mining scenario may be controlled by *depth of extraction, mining intensity* and *processing return technique*.

2.3.2 DEFINING THE CONDITIONAL PROBABILITIES

Within a BN, the magnitude of impacts is illustrated through conditional dependencies which describe the strength of relationships between variables in the model (Pearl 1986). In the case of discrete variables, conditional probabilities are summarised in a conditional probability table (CPT) which describes the distribution of the values of the child node for every combination of states of the parent nodes, in this case, the probability of biological responses under the different magnitude of pressures (Fig. 4).

With an increasing number of parent variables, the number of conditional probabilities grows exponentially, making the estimation of probabilities both time-intensive and cognitively challenging (Morales et al. 2008; Werner et al. 2017). In **paper III,** I used the ACE application by Hassall et al. (2019) to initialise the conditional probability tables (CPTs). The graphical interface of the application, run via R software, provides a starting point for defining the shape of a conditional probability distribution by allowing ranking the direction and magnitude of connections between network nodes and populating the table through a scoring algorithm. The application further allows documenting the level of expertise of the person making the assessment for an additional metric of certainty.

After initialisations, the prefilled CPTs were evaluated and adjusted in two sessions with the experts. CPTs were incorporated in the DAG coded in R for a full BN.



Change in biomass \ Sedimentation	Low	Medium	High
0-10%	0.5	0.1	0
11-30%	0.3	0.3	0.1
31-50%	0.1	0.3	0.1
51-80%	0.1	0.2	0.3
81-100%	0	0.1	0.5

Figure 4. Schematic description of the conditional probabilities within two nodes in a BN. In this example, the change in biomass of filter feeding organisms is conditionally dependent on the levels of sediment deposition. The conditional probability table (CPT) describes the values of both the parent and the child node, summarising the probability distribution of mortality of benthic fauna under different levels of sedimentation.

After parametrisation of the network, the BN may be queried by setting certain variables into a specific state and inferring the probability distribution of other variables of interest given that evidence.

Following the Bayes rule, BN models enable computing the posterior probability of events given new evidence. Enabling a two-way flow of information, the network may also be queried to evaluate which evidence would be the most likely to explain a given outcome (cause-effect relationship), for instance, the posterior probability of changes in classes of benthic fauna given a certain set of operational parameters. In this manner, the model may be developed into a decision model to evaluate which measures, environmental conditions, and technologies should be in place in order to e.g. minimise the loss of benthic fauna to below a certain threshold. The BN developed in **paper III** was used to evaluate two scenarios with a different combination of variable states describing the mining operation in terms of the depth of extracted sediment, mining intensity, and release of harmful substances to evaluate the mortality of benthic fauna under the pressures stemming from them.

2.3.3 STRUCTURAL LEARNING

In paper **IV**, survey data collected through an online questionnaire was analysed with BNs to learn the structural connections in the data to find dependencies between the studied variables (general worldviews and values, symbolic values, care for environments, and risk perceptions). Application of structural learning algorithms allows exploring the structure of the data by reducing its dimensions and retaining only the strongest connections, giving insight into the most relevant connections between variables (Barber 2012).

In this study, we were interested in the conditional dependencies between general worldviews and values, symbolic value scores, care for environments, and risk perceptions to evaluate how these concepts related to each other. The data were divided into four classes based on the questions targeting each of the four studied environments (the deep sea, Moon, Antarctica, and terrestrial environments) to study whether similar patterns between survey items appeared in all of the environments.

Although BNs are most often defined through directed acyclic graphs with an interest in the direction of the connection between variables, BNs may also be applied simply to illustrate the connections (or lack of them) between variables. An algorithm-learnt BN can be seen as a lower-dimensional representation of the data, which retains the strongest dependencies in the data, accounting also for associations between multiple variables, while abstracting out weak correlations (Barber 2012). BNs can thus be used to understand complex multivariate relationships, offering a more robust method to evaluate dependencies between multiple variables than simple linear correlations by accounting for non-linear connections. In paper **IV**, BNs are applied without interpretation that the arcs represent causal relationships between variables and use network structure to indicate conditional independence relationships and probabilistic properties (Pearl 2009; Scutari and Denis 2014).

To learn the conditional dependence structure from the data, we applied the hill-climbing algorithm using the package *bnlearn* (Scutari 2009) in R (R, 2019). Bayesian Dirilecht Equivalent (BDe) was used as optimization score by the algorithm to learn the most optimal network structure, as it deals better with small sample sizes without penalizing network complexity (Nielsen and Jensen 2009). Structural uncertainty was evaluated with non-parametric bootstrapping with 2500 samples (Broom et al. 2012). We set a default threshold of 0.7 for arc significance, meaning that only arcs that appeared in 70 % of the networks were retained in the final averaged network. All analyses were performed in R 3.6.1 (R, 2019).

3 RESULTS

3.1 NARROW FOCUS OF SEABED DISTURBANCE STUDIES

Paper **I** presents a synthesis on the impacts of seabed mineral extraction on marine ecosystems and evaluates the scope and methods that have been used to assess the impacts. We identify impacts that have been thus far examined in *in situ* experiments or through modelling, and outline effects that have been left unaddressed but are crucial to gaining a comprehensive view of the environmental risks of seabed mining.

The results of the literature review show that impacts of SBM have been addressed mainly through changes in benthic fauna, with little consideration to the water column and other ecosystem components. We also find that the scarcity of information on the ecological and geochemical role of seafloor mineral deposits (Vanreusel et al. 2016; Zhamoida et al. 2017; Kotilainen et al. 2018) impedes detailed estimates of the consequences of their removal to ecosystem functioning via e.g. habitat loss and biogeochemical processes. Without this information, the recovery of or impacts on associated organisms cannot be sufficiently estimated.

The results of the review outline a causal framework for linking the pressures from mining to changes in the affected ecosystem components, and further to the ecosystem functions and services. Describing the impacts through specific pressure-state change pathways widened the amount of available information for studying the effects of mining on different components of the marine ecosystem. We further recognise the need to account for the cascading effects in ecosystem state to changes in ecosystem services and their subsequent impacts on welfare in comprehensive risk assessments. With the causes and effects illustrated throughout the impact statement process, further analyses of the risks may be carried out.

3.2 DISTRIBUTION OF MINERAL CONCRETIONS MORE EXTENSIVE THAN EXPECTED

In study **II,** we estimate the spatial variability and abundance of FeMn concretions in Finnish marine areas in the northern Baltic Sea. Concretions were observed in all sub-basins of the study area and are predicted to form distinct belts extending from the Bothnian Bay to the Gulf of Finland. The most abundant deposits are reported from the Gulf of Finland and the Kvarken area in the Gulf of Bothnia, forming at the fringes of deeper basins in oxic areas prone to occasional hypoxia. Concretions were present in depths of 0–75 m in a variety of seafloor types, from muddy bottoms to rocky seafloors.

The developed models were successful in predicting both concretion occurrence and abundance with excellent model performance compared to the validation data. When extrapolated to the full seascape in the Finnish marine areas, the modelling exercise produced prediction maps for concretions occurrence and abundance. Based on the modelling results, we estimate that at least 11 % of the Finnish seafloors host suitable environments for FeMn concretion formation.

3.3 MULTIPLE PRESSURES AND HIGH UNCERTAINTY ON ECOSYSTEM RESPONSES MARK SBM

In study **III,** we outline the cause-effect pathways related to SBM activities through a series of interviews with a multidisciplinary group of experts. The interviews resulted in 11 individual causal maps. After harmonising variables and expert comments on the causal network structure, the combined conceptual model has 53 variables and 96 connections between them. The results outline that SBM activities affect all levels of the marine ecosystem, spanning from acute, local effects to more long-term impacts that extend beyond the mining site. In general, there was strong consensus between experts on the most important impact pathways and causal connections, and the differences between experts were attributed to the number of variables and level of detail in different processes regarding the impacts of mining.

The BN model developed based on the combined causal network was used to provide quantitative estimates of mortality of benthic fauna. We used the model to evaluate various mining scenarios in order to identify key factors related to the impacts as well as the uncertainty associated with them.

The results from model queries show that the direct extraction of seabed substrate and concretions had the largest impact on the direct mortality of the benthic fauna. In terms of indirect effects, the release of ecologically significant levels of toxic substances from the sediment had the highest impact on the mortality of benthic fauna. Overall, the experts assessed the relative mortality of benthic fauna to be highly variable, showing low levels of certainty on the cumulative effects of multiple pressures.

3.4 SYMBOLIC VALUES SHAPE CARE ABOUT MINING IN REMOTE ENVIRONMENTS

Paper **IV** presents a novel theoretical framework to study factors contributing to people's care for remote environments and links this to the perceived risks of anthropogenic activities. Our results show that people's underlying values and emotions, more so than knowledge or worldviews, shape people's environmental care. These values further mediate perceptions of societal and environmental risks of mining.

Despite its remoteness, we found that the deep sea does matter to people. Although people knew even less of the deep sea than the Moon, they perceive it likely that mining will take place there in the future. Interestingly, people's self-assessed knowledge about an environment had little to do with how much they care about it. In turn, we find that the emotions an environment evokes are much more important in predicting care for an environment.

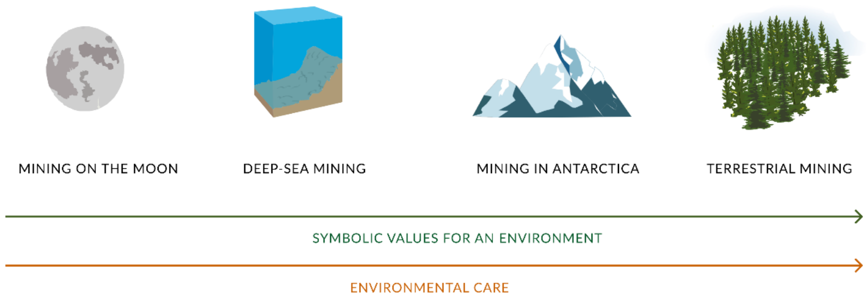


Figure 5. Symbolic values for an environment and the stated environmental care for the four studied environments.

We found that symbolic values shape people's environmental care and that the overall symbolic value attributed to each of the environments differs (Figure 5). While deep-sea mining was perceived riskier than mining in the other remote environments, people care less about the negative impacts on the deep-sea environment. Overall, the majority of respondents stated that they care a lot or very much about the deep sea.

4. DISCUSSION

The expanding industrial use of the ocean space and resources occurs in parallel with increasing expectations of its benefits to human societies (Halpern et al. 2012; Lee et al. 2020). This increasing industrialisation calls for more comprehensive assessments on the risks associated with new activities to understand any negative environmental effects compromising these contributions (Fleming et al. 2019; Hodgson, et al. 2019). In this thesis, I studied what can be done to improve sustainability in the marine realm by taking a predictive approach to risks of emerging maritime industries (Fig. 6). I use the case of seabed mining to explore the knowledge needs to outline the risks, how to quantify them based on existing knowledge, and the factors affecting how they are perceived.

4.1 ANSWERING RESEARCH QUESTIONS

IMPROVING METHODOLOGY FOR COMPREHENSIVE RISK ASSESSMENTS

The lack of experimental evidence from seabed mining and scarcity of baseline data limit the implementation of traditional impact assessments for potential future SBM activities (Washburn et al. 2019). In this thesis, I explored how to evaluate the impacts of SBM while accounting for this lack of evidence and data. Drawing on the results of a literature review and expert interviews, I developed an approach to obtain a more comprehensive view of the impacts and demonstrate how to use it in an operational setting for more specific cases, presenting the first systematic evaluation of the ecological risks associated with seabed mining activities (I, III).

Although environmental impact assessments are based on the idea of cause and effect, the use of explicit causal modelling has been little used in formal EIA and ERA practices (Perdicoúlis and Glasson 2006; Perdicoúlis and Glasson 2012; Kaikkonen et al. 2021). This thesis demonstrates how qualitative information may be used to move towards a quantitative assessment by using a causal probabilistic approach to estimate the impacts and to improve transparency of the assessment.

While the potential impacts of seabed mining have been addressed in an increasing number of studies, this thesis offers a much-needed approach to synthesise empirical findings and to highlight the many uncertainties around the impacts of mining to support operational risk assessments (Pollino et al. 2007; Durden et al. 2018; Hyman et al. 2021). These results show that the knowledge related to the impacts of seabed mining is still low, calling for further research on the risks of mining to specific ecosystem components. The findings particularly highlighted the challenges in conceptualising the spatiotemporal complexity and multidimensional interactions related to anthropogenic impacts (I, III, Hodgson et al. 2019). The modularity of the applied modelling methods enables including spatial and temporal dynamics which are needed to account for the overall impacts of the activities and can be updated to account for new information on the ecological consequences of specific pressures to organisms (e.g. Cummings et al. 2020).

ADVANCING KNOWLEDGE OF THE ENVIRONMENT UNDER PRESSURE

Understanding the characteristics of the environment that will be affected by external pressures sets the basis for assessing the impacts of any activity. Paper II demonstrated how to advance knowledge on an environment and resource targeted by human activities using a data-driven approach. Drawing on an extensive dataset from a national underwater inventory programme, both the empirical observations and the resulting predictions from spatial modelling revealed that FeMn concretions are more widespread than previously estimated (Glasby et al. 1997). Despite local variation in FeMn concretion formation processes (Zhamoida et al. 2007; Baturin 2010), the created models were successful in predicting the occurrences of concretions across the study area, and illustrate that environmental conditions provide a useful proxy for estimating the distribution of biogeochemical seabed formations. Spatial modelling approaches contribute towards more knowledge of underwater seascapes for both conservation planning and sustainable use of marine resources (Virtanen 2020).

For further risk assessments, these results outline under what kind of conditions and where extraction would likely take place and allow for further studies on their characteristics. To advance understanding of the overall footprint of the mining activity and recovery potential of the biological communities within concretion fields, it is crucial to affirm the ecological role of concretions in addition to their distribution (II, III, Lotze et al. 2011; Gollner et al. 2017). Benthic marine landscapes found in topographically complex seabed areas have been observed to have higher species diversity than homogenous regions (Kovalenko et al. 2012; Kaskela et al. 2017) and especially large concretions could provide a habitat for both mobile and sessile benthic fauna (Leinikki 2020). The substantial area potentially covered by FeMn concretions emphasises the importance to examine their ecological role to estimate the consequences of their removal to marine ecosystems. This information would further allow to estimate the overall trade-offs of mineral extraction, if the economic resource potential of FeMn were to be compared with the value of the ecosystem functions provided by these underwater environments.

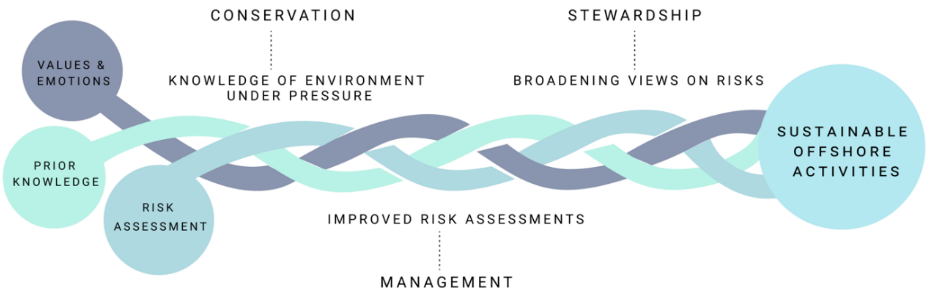


Figure 6. Contributions of the thesis to improving views of environmental risks of emerging maritime activities to support sustainability in the marine realm.

BROADENING VIEWS ON THE RISKS OF MINING

Given the rapid industrialisation across the world's oceans, evaluating public perceptions of human activities in offshore areas is essential for sustainable ocean governance. The deep sea offers a fascinating theoretical framework to study how we relate to remote and unfamiliar natural environments to explore sustainability in the marine realm within coupled social-ecological systems (Leach et al. 2018; Levin et al. 2020). In paper IV, we present a novel framework for unravelling factors contributing to environmental care and aim to answer the question ‘even if we estimate the risks, will people care about them?’

Much of the previous research pertaining to environmental care has relied on metrics based on people’s sense of place (Jones et al. 2016; Torres et al. 2016). These approaches have been problematic for studying public perceptions of unfamiliar places, as they cannot rely on instrumental and rational approaches to values. While many previous analyses would group environmental care under intrinsic values (Kagan 1998; Chan et al. 2016; Batavia and Nelson 2017), we show that measuring only the intrinsic value of an environment is not sufficient in explaining the level of environmental care to the extent that the combination of symbolic values has allowed. Paper IV thus contributes to the scholarship on environmental care and can offer theoretical considerations for evaluating public perceptions of other offshore activities.

These findings refute the misconception that because the ocean, and particularly the deep sea are perceived as dark and scary, as widely portrayed in popular culture (Hackett and Harrington 2018), people would not care about the deep sea (Jamieson et al. 2020). Although in this thesis I was particularly interested in the deep sea due to its extreme remoteness and the global nature of its governance, these results may also be applied to other offshore environments. The perceived remoteness of an environment is not directly ascribed to its physical remoteness, and many coastal habitats may also be perceived as unfamiliar (Barr and Kliskey 2014). This aspect of care is particularly interesting for many marine environments that may not be considered very charismatic (Ankamah-Yeboah et al. 2020), including the FeMn concretion fields studied in this thesis (II). In this respect, the results of paper IV are exciting when considering the ongoing research on conservation behaviours and environmental stewardship (e.g. West et al. 2018; Bennett et al. 2018). Unravelling the factors that contribute to the care for the studied remote environments, whether cultural or spiritual, requires a more in-depth approach.

4.2 IMPLICATIONS FOR GOVERNANCE OF SEABED RESOURCES

Evaluating the role of scientific knowledge in SBM governance presents a unique context in which science does not (yet) need to play catch up with the industry. As commercial-scale mining has not started yet, this provides an opportunity to evaluate what the risks are before large-scale activities begin, whether they should be permitted, and what additional knowledge is needed for sustainable decision-making processes. An illustrative example of an opposite situation is the fishery of the deep-sea fish orange roughy in New Zealand waters, which was heavily fished in the 1980s (Clark 2001). As a result of limited scientific information on the species and subsequent lack of appropriate regulation, the fishing industry nearly depleted the stocks of the deep-dwelling species before actions were taken to limit fisheries.

In the context of SBM, estimating the potential impacts of specific pressures and their likelihoods would enable adequate management measures to be taken before large-scale activities begin (Cuvelier et al. 2018). While previous studies have shown SBM to cause extensive damage to seafloor habitats, (Hiddink et al. 2019; Simon-Lledó et al. 2019; Vonnahme et al. 2020), estimating the impacts and accounting for the knowledge gaps with a probabilistic approach can either support a moratorium in line with a precautionary approach, or provide information for more comprehensive risk management plans for potential future mining activities (Barbier et al. 2014).

To do this, the results from model simulations in alternative mining scenarios should be compared to the policy targets regarding changes in ecosystem status. The results of this work thus contribute to evaluating trade-offs from mining and support permitting and regulation processes by providing more comprehensive estimates of the environmental impacts of seabed resource use. As EIAs have been scrutinised for their lack of transparency, causal networks will help communicate the rationale behind the estimates (Carriger et al. 2018). This more holistic view of the ecological risks is in line with the conceptual EBM approach to risk assessment (Holsman et al. 2017) and could be applied both in industry-wide studies on environmental and economic sustainability of a novel maritime sector as well as individual projects applying for environmental licenses.

Considering the challenges in estimating ecosystem responses to external disturbances, perfectly predicting environmental impacts from SBM is an unrealistic objective for scientific research, particularly regarding the knowledge needs to support governance of marine resources (Schindler and Hilborn 2015). Therefore, information on the fact that we are unable to estimate the impacts is equally valuable (Sahlin et al. 2021) and supports the application of the precautionary approach. Evaluating which impacts are hardest to estimate and to what extent it is possible to reduce uncertainty are crucial for guiding future research and extraction guidelines. In a case where uncertainties are considered too high, permits could be made to be conditional on improved knowledge by allowing only one test mining operation to proceed until impacts have been documented in more detail (Smith et al. 2020), urging the industry to carry out further studies. A systems approach, such as the one described in this thesis, can support such adaptive management of mining operations (Jaeckel 2016; Durden et al. 2017).

In addition to the environmental considerations outlined in this thesis, there are many societal risks stemming from offshore industries which are still insufficiently recognised (Bennett et al. 2021). When considering the broader implications of these results and any subsequent decisions on whether seabed minerals are a potential source of raw materials, public perceptions and views of the acceptability of the risks are a key consideration in guiding development of SBM activities. It is increasingly clear that only focusing on the technical details of an activity risks disregarding people’s values in decision-making, potentially resulting in conflicts and poor outcomes for both the environment and the society (Wolsink 2010; Sultana 2015). It is thus essential to acknowledge how the scientifically assessed results regarding the risks will be perceived by both the decision-makers and the public.

With concerns on the impacts of terrestrial mining, the comparison between ocean mining and land-based mining is a recurrent consideration in the literature and underpins much of the discussion on whether seabed mining ought to proceed (Beaulieu et al. 2017; Childs 2019; Levin et al. 2020). As outlined in the results of this thesis, any such considerations will ultimately depend on how we view these different environments and what kind of risks to the marine environment people are willing to accept and how their values for different unfamiliar environments affect that (IV). The direct comparison of SBM to land-based mining is therefore untenable, as people present different views about environments that are perceived as remote and will not evaluate the risks similarly in these different contexts.

4.3 TOWARDS MORE SUSTAINABLE USE OF OCEAN SPACE AND RESOURCES

Given the difficult access to the deep sea, current governance of the deep sea space is viewed through mostly technocratic narratives (Alaimo 2019; Reid 2020). Similarly, the use of scientific knowledge in the overall ocean governance has focussed on mapping of its resources and understanding ecosystem functioning, framing the challenges related to management of marine resources as only technical (Campbell et al. 2016). In turn, human values and emotions are often dismissed as irrelevant in contrast to the environmental and economic risks in environmental decision-making (González-Hidalgo and Zografos 2020).

One reason for the predominantly technical views of the marine environment is that the oceans have long been considered out of sight, out of mind (Hannigan 2016), untouched and remote to humans. This framing of the oceans as an uncontested space for exploitation has led to the construction of the oceans primarily as a resource to be exploited through its mineral resources, food sources, potential biomaterials for pharmaceuticals, and as an endless supplier of other materials (Reid 2020). These harmful representations of marine space have long supported the view that the ocean is too large to be harmed by human activities (Carson 1951; Lubchenco and Gaines 2019).

As the views about ocean space have direct implications for policies and governance (Neimanis et al. 2015), understanding these imaginaries and acknowledging the representations about the ocean is critical to shape decision-making that ensures looking after marine environments (Gee 2019). To date, broader consideration of human values has had only few applications in ocean governance (e.g. Bidwell 2017) as opposed to economic values. However, these are likely to become more important as the industrial interest in the oceans will require increased focus on the acceptability of operations to inform decision-making on what kind of activities people will support or oppose (Voyer and van Leeuwen 2019). The combined findings of this thesis can serve in more broad-scale analysis of perceived positive and negative impacts of SBM to further make more value-based decisions on if these impacts are at acceptable levels, and to consider whether SBM contributes to a global net benefit as an option for critical raw materials (Haugan et al. 2020).

Ensuring sustainability in the marine realm requires improved stewardship through careful and responsible management of the environment (Bennett et al. 2018; Mathevet et al. 2018). We are putting more pressures on the ocean with increasing expectations of its goods and services for human well-being, both economically and increasingly through other contributions. It is now deemed unlikely that the business-as-usual development of maritime sectors can deliver the expectations of the Blue Economy while ensuring protection of the marine environment (Novaglio et al. 2020). More holistic approaches to risks are required as a part of an integrative approach to ocean use to aid sustainable management of marine resources. This entails a broader consideration of economic, societal, and governance dimensions of offshore activities (Bennett et al. 2019), with environmental risks only one part of the puzzle.

Improved stewardship of the marine environment is dependent on the recognition that while the ocean is vast and remains to a large extent out of sight, the ongoing degradation of the marine environment can no longer be ignored (Lubchenco and Gaines 2019). If people do not care about risks to the environment, the impacts can get out of control. As the conversation around the Blue Economy and use of ocean resources evolves, many offshore environments will become more and more central to this, and it is crucial that societal perceptions, values, and attitudes towards them and the risks posed by human activities are part of the discourse.

5 CONCLUSIONS

Due to increasing demand for raw materials, commercial seabed mining activities are now considered imminent across the world's oceans. In this thesis, I explored how predictive risk assessments can inform marine resource governance and support environmental management plans for emerging maritime activities. I use seabed mining as a case study to outline knowledge requirements for assessing the environmental risks and the factors affecting public perceptions of them. The results present an alternative to currently used risk assessment methods, offering tools for more anticipatory and transparent decision making by drawing on existing knowledge. By highlighting the many uncertainties associated with environmental impacts of mining activities, these findings have direct uses and implications for guiding both scientific research regarding the risks of mining and policy recommendations. The combined findings of this work suggest that it is fundamental to both increase knowledge of the environment that will be affected to better assess the risks, and to account for the underlying values and emotions towards the marine environment to fathom how those risks will be perceived by both decision makers and the public. To avoid unbridled expansion of human activities in the oceans, these results highlight the need to engender stronger connection and greater awareness of marine environments to enhance feeling of care and to nurture ocean stewardship for equitable and sustainable Blue Economy.

ACKNOWLEDGEMENTS

This work would not have been possible without the overwhelming support and sharing of knowledge, ideas, and perspectives with all the wonderful people I have met. I have been incredibly fortunate to surround myself with people who have been interested in my work and have offered their help all the way through. I've knocked on so many doors during the past four years, hence the length of this section, which is by far my favourite to write. I express my deepest gratitude especially to the people mentioned here, but also to many others who have helped me along the way or taken a moment to discuss and share ideas. These encounters have been the best part of this whole project.

First, I wish to thank Professor Anna Metaxas for agreeing to serve as the opponent for the defence. For many years, I have secretly dreamt of the deep ocean and whether my work could in any way contribute to ongoing work to protect deep-sea ecosystems. I could not be happier for the chance to discuss these topics with you. On a side note, it also brings me great joy to have discovered your ongoing research work on kelp, my favourite organism on the planet.

A thousand thanks to my supervisors, I could not have asked for a better team to steer and accompany me through the surge. Kirsi, I am in awe of your enthusiasm, energy and vision for new research ideas and bringing clarity to everything you touch. In addition to being a kick-ass scientist with an impeccable eye for operating in the science-policy interface, thank you for all your encouragement and caring when I was about to lose focus. Sakke, thank you for the opportunity to carry out this work, for being on board with my ideas and letting me see them through. I have learnt so much! Laura, I cannot express how happy I to have had you oversee my work. Your advice and vision on everything modelling related has been beyond what I could ever ask for, but most importantly you are the best role model for making my way through the research-science jungle. From the bottom of my heart, thank you.

I wish to express my deepest gratitude to my thesis advisory committee: Joanna Norkko, Samu Mäntyniemi and, Samuli Korpinen, it has been a privilege to have your views on my work. You support and advice has meant the world to me, thank you! My pre-examiners, Sabine Gollner and Serena Hamilton, I am honoured and thankful for the interest you took in my work.

Jukka, thank you for agreeing to serve as the custos and the responsible professor for all things related to this thesis and my postgraduate studies. In addition to signing all the papers, helping with chaotic field work planning, and borrowing keys, thank you for your help with getting this work to the finish line and for your relaxing energy.

Warmest thanks to Riikka for your support at the beginning of the thesis. Without your enthusiasm, I never would have taken on this project, and I'm thankful for all the times you succeeded in phrasing my thoughts and ideas better than I ever could have.

I have shamelessly used this PhD project to reach out to talented people I wanted to work with. Ale, thank you for introducing me to the world marine geology and above all for the fun collaborations. When I started out, it was very clear I didn't have a clue about marine minerals, so this work would not be anything without your time and interest, ranging from hanging out at geology conferences to collecting samples together (and all the time in between waiting for the conditions to get better). It seems like geologists do have more fun! Elina, I'm so glad to have crossed academic paths with you. Thank you for being the most wonderful collaborator, and above all for your friendship, support, and advice. Looking forward to many collaborations and brainstorming sessions together! Thank you to my co-authors Henrik Nygård and Anna Törnroos for jumping in with your expertise in all things benthic ecology, and for all the interesting discussions in various events. Many thanks to Juho for your expertise in underwater surveys and collaboration. Inari, thank you for friendship, support, laughs, and great ideas (DiscCI!!). Special thanks for the snacks and hugs when most needed. Ingrid, thank for your contagious creativity and for diving into a collaboration out of the blue - seems like the best ideas do start from random discussions! I am so grateful for your friendship and

support in helping me navigate through a field completely new to me. It's been a lot of fun and I hope it's not the end!

I wish to thank all my brilliant colleagues from the extended Fisheries and Environmental Management & Marine Risk Governance research groups during the past four years: Tuuli, Emilia, Mirka, Jussi, Kelsey, Annukka, Maisa, Lauri, Dunja, Magnus, Miia, Mika, Päivi, Suvi, Anna, Oula and Eduardo. Thank you for all the inspiration, advice, and skill sharing sessions throughout the years!

It's been a privilege to share my working days with inspiring colleagues at the Aquatic Science/Ecosystems and Environment Research Programme, both in Helsinki and Tvärminne. From the beginning of my studies in Helsinki, I've received endless encouragement from Janne. Thank you for pushing me to venture on a research career and for the continuous cheering and good times. Jaanika, I cannot admire your energy, kindness, and dedication towards teaching enough, thank you for all your support and advice. Thanks to also Leena, Aleksandra, and Jyrki, among others, for your company during teaching. Thank you Elli for literally diving into FeMn concretion fields with me – it may have been dark and muddy, but also a lot of fun. I owe great thanks to Christopher Raymond for his careful advice on planning the theoretical framework for the online survey study. Tom, thank you for the endless encouragement and your generous help, be it with biogeochemistry, proof-reading, or survival tips for both life and research. Above all, thank you for your friendship.

I wish to extend my thanks to SYKE Marine Research Centre for hosting me as a visiting researcher and for providing access to the laboratory facilities. Thank you to all the colleagues for nice discussions and sharing of ideas during coffee breaks, conferences, and field work. I am especially grateful for everyone who has kindly gifted me cool FeMn concretion samples. The greatest thank-you goes to Okko for the countless hours of science therapy and hunting down obscure data sheets – I am so lucky to have you as a friend. I also express my appreciation to my colleagues at HELCOM, I have learned a great deal from you!

The financial support for this thesis was provided by the Strategic Research Council of the Academy of Finland by the Smartsea project. It's been a lot of fun being involved in such a diverse project with many passionate scientists and having the chance to learn so much. I particularly wish to thank Make for the fresh ideas and encouragement, and Jyrki for the advice on sand extraction.

Despite my background in natural sciences, my own data collection for this work only involved sampling humans. My research would not have been possible without the many experts involved in the risk modelling. Sebastian Valanko, Aarno Kotilainen, Anna Törnroos, Alf Norkko, Lena Bergström, Jouni Lehtoranta, Meri Kallasvuo, Ilppo Vuorinen, Henry Vallius, Henrik Nygård, and Kirsi Kostamo, thank you for your time and great discussions, I enjoyed talking with each of you. I thank everyone who helped distribute the online survey for paper IV and took the time to answer our queries. This study literally would not have been possible without your help. I further wish to acknowledge all the planners and field scientists who have been involved in collecting the VELMU data that enabled our study on FeMn concretion distribution.

I was incredibly lucky to have spent a few months at the Deep-Sea Ecosystems and Fisheries Group at NIWA. Never have I felt so welcome and instantly at home as I did at the Wellington office, thanks to all the wonderful colleagues. Thank you, Malcom Clark, for having me over and for the opportunity to dive into the fascinating world of deep-sea ecology. Special thanks to Ashley Rowden, Dave Bowden, Daniel Leduc and Judi Hewitt for your input on the risk modelling work, and to Savannah, Katie and Di for your friendship. I am so grateful for also having had the chance to visit CSIRO and Centre for Marine Socioecology in Hobart. Thank you to all the colleagues for providing such an inspirational environment and for leading the way for interdisciplinary marine science. I also wish to extend my thanks to the IMBeR community for inspiration and wider views on marine science. Thank you especially to my low-toe five pals for continuous support and inspiration.

My friends, you are the salt and sugar of my life. Heidi, Eevert, Viivi, Paula, Sam, Maarit, Annina, Laura, the extended maksa-group, all the dinner party companions, and my cousins, thank you for your love, support, and interest in my work during all these years – especially for shining a light on the most important things in life. In addition to fantastic discussions, this thesis work has been exquisitely fuelled by excellent music, home-brewed beer, and great parties. Thank you, Saara, for your sharp eyes in editing paper IV, and most importantly for post-dance class soul healing and all the party times. Anni, thank you for sharing all the joys and bumps of life with me, for carefully planning the cover art, and for always being up for a little adventure.

My love for the sea was planted in me since childhood. I thank my grandparents for everything they taught me, after living and breathing the sea during their many adventures. Kiitos äiti for your love, support, encouragement, and advice with all the research-related matters. Kiitos isi for all the adventures, reminding me to be curios and keep dreaming. Ninni, thank you for your love and energy. I must have done something extraordinary in the past life to have the best sister anyone could hope for.

Samy, thank you for your love for life, endless curiosity, and for being the most beautiful and creative soul there is. I am so grateful for your advice, steady support, and patience listening to my stories of the sea and science. What a joy it is to get to spend this life with you, merci mon amour.

REFERENCES

Aanesen M, Armstrong C, Czajkowski M, Falk-Petersen J, Hanley N, Navrud S. 2015. Willingness to pay for unfamiliar public goods: preserving cold-water coral in Norway. Ecol Econ. 112:53–67.

Alaimo S. 2019. Introduction: Science Studies and the Blue Humanities. Configurations. 27(4):429–432.

Ankamah-Yeboah I, Xuan BB, Hynes S, Armstrong CW. 2020. Public Perceptions of Deep-Sea Environment: Evidence from Scotland and Norway. Front Mar Sci. 7. doi:10.3389/fmars.2020.00137. [accessed 2020 Mar 2]. https://www.frontiersin.org/articles/10.3389/fmars.2020.00137/abstract.

Armstrong CW, Foley NS, Tinch R, van den Hove S. 2012. Services from the deep: Steps towards valuation of deep sea goods and services. Ecosyst Serv. 2:2–13.

Ascough Ii JC, Maier HR, Ravalico JK, Strudley MW. 2008. Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. Ecol Model. 219(3–4):383–399.

Aven T, Renn O. 2010. Risk Management and Governance: Concepts, Guidelines and Applications. Berlin Heidelberg: Springer-Verlag (Risk, Governance and Society).

Barber D. 2012. Bayesian reasoning and machine learning. Cambridge University Press.

Barbesgaard M. 2018. Blue growth: savior or ocean grabbing? J Peasant Stud. 45(1):130–149.

Barbier EB, Moreno-Mateos D, Rogers AD, Aronson J, Pendleton L, Danovaro R, Henry L-A, Morato T, Ardon J, Van Dover CL. 2014. Protect the deep sea. Nature. 505:475–477.

Barr BW, Kliskey AD. 2014. Perceptions of wilderness and their application to ocean and coastal waters. Ocean Coast Manag. 96:1–11.

Batavia C, Nelson MP. 2017. For goodness sake! What is intrinsic value and why should we care? Biol Conserv. 209:366–376.

Batker D, Schmidt R. 2015. Environmental and social benchmarking analysis of the nautilus Minerals Inc. Solwara 1 Project. https://www.nautilusminerals.com/irm/content/pdf/eartheconomics-reports/earth-economics-may-2015.pdf.

Baturin GN. 2010. Element Composition of Ferromanganese Concretions in the Black Sea. Oceanology. 50(1):83–92.

Baturin GN, Dubinchuk VT. 2009. Composition of Ferromanganese Nodules from Riga Bay (Baltic Sea). Oceanology. 49(1):111–120.

Beaulieu SE, Graedel TE, Hannington MD. 2017. Should we mine the deep seafloor? Earths Future. 5(7):655–658.

Bennett NJ, Blythe J, White CS, Campero C. Blue growth and blue justice: Ten risks and solutions for the ocean economy. Mar Policy. 125:104387.

Bennett NJ, Cisneros-Montemayor AM, Blythe J, Silver JJ, Singh G, Andrews N, Calò A, Christie P, Di Franco A, Finkbeiner EM. 2019. Towards a sustainable and equitable blue economy. Nat Sustain.:1–3.

Bennett NJ, Whitty TS, Finkbeiner E, Pittman J, Bassett H, Gelcich S, Allison EH. 2018. Environmental Stewardship: A Conceptual Review and Analytical Framework. Environ Manage. 61(4):597–614.

Bickerstaff K. 2004. Risk perception research: socio-cultural perspectives on the public experience of air pollution. Environ Int. 30(6):827–840.

Bidwell D. 2017. Ocean beliefs and support for an offshore wind energy project. Ocean Coast Manag. 146:99–108.

Boström K, Wiborg L, Ingri J. 1982. Geochemistry and origin of ferromanganese concretions in the Gulf of Bothnia. Mar Geol. 50(1–2):1–24.

Bouman T, Steg L, Kiers HAL. 2018. Measuring Values in Environmental Research: A Test of an Environmental Portrait Value Questionnaire. Front Psychol. 9, 564.

Boyes SJ, Elliott M, Murillas-Maza A, Papadopoulou N, Uyarra MC. 2016. Is existing legislation fit-for-purpose to achieve Good Environmental Status in European seas? Mar Pollut Bull. 111(1–2):18–32.

Breiman L. 2017. Classification and regression trees. Routledge.

Broom BM, Do K-A, Subramanian D. 2012. Model averaging strategies for structure learning in Bayesian networks with limited data. BMC Bioinformatics. 13(Suppl 13):S10.

Brown G, Raymond C. 2007. The relationship between place attachment and landscape values: Toward mapping place attachment. Appl Geogr. 27(2):89–111.

Brown G, Reed P. 2000. Validation of a forest values typology for use in national forest planning. For Sci. 46(2):240–247.

Bruner JS, Postman L. 1948. Symbolic value as an organizing factor in perception. J Soc Psychol. 27(2):203–208.

Burgman M. 2005. Risks and decisions for conservation and environmental management. Cambridge University Press.

Campbell LM, Gray NJ, Fairbanks L, Silver JJ, Gruby RL, Dubik BA, Basurto X. 2016. Global oceans governance: New and emerging issues. Annu Rev Environ Resour. 41:517–543.

Carriger JF, Barron MG, Newman MC. 2016. Bayesian Networks Improve Causal Environmental Assessments for Evidence-Based Policy. Environ Sci Technol. 50(24):13195–13205.

Carriger JF, Dyson BE, Benson WH. 2018. Representing causal knowledge in environmental policy interventions: Advantages and opportunities for qualitative influence diagram applications. Integr Environ Assess Manag. 14(3):381–394.

Carson R. 1951. The Sea around us.

Carver R, Childs J, Steinberg P, Mabon L, Matsuda H, Squire R, McLellan B, Esteban M. 2020. A critical social perspective on deep sea mining: Lessons from the emergent industry in Japan. Ocean Coast Manag. 193:105242.

Chan KM, Balvanera P, Benessaiah K, Chapman M, Díaz S, Gómez-Baggethun E, Gould R, Hannahs N, Jax K, Klain S. 2016. Opinion: Why protect nature? Rethinking values and the environment. Proc Natl Acad Sci. 113(6):1462–1465.

Chen SH, Pollino CA. 2012. Good practice in Bayesian network modelling. Environ Model Softw. 37:134–145.

Childs J. 2019. Greening the blue? Corporate strategies for legitimising deep sea mining. Polit Geogr. 74:102060.

Clark M. 2001. Are deepwater fisheries sustainable?—the example of orange roughy (Hoplostethus atlanticus) in New Zealand. Fish Res. 51(2–3):123–135.

Clark MR, Durden JM, Christiansen S. 2019. Environmental Impact Assessments for deep-sea mining: Can we improve their future effectiveness? Mar Policy 114.

Clayton S. 2003. Environmental identity: A conceptual and an operational definition. Identity Nat Environ Psychol Significance Nat.:45–65.

Clayton S, Myers G. 2015. Conservation psychology: Understanding and promoting human care for nature. John Wiley & Sons.

Cummings VJ, Beaumont J, Mobilia V, Bell JJ, Tracey D, Clark MR, Barr N. 2020. Responses of a common New Zealand coastal sponge to elevated suspended sediments: Indications of resilience. Mar Environ Res. 155:104886.

Cuvelier D, Gollner S, Jones DOB, Kaiser S, Arbizu PM, Menzel L, Mestre NC, Morato T, Pham C, Pradillon F, et al. 2018. Potential Mitigation and Restoration Actions in Ecosystems Impacted by Seabed Mining. Front Mar Sci. 5. 467.

De'Ath G. 2007. Boosted trees for ecological modeling and prediction. Ecology. 88(1):243–251.

deFur PL, Kaszuba M. 2002. Implementing the precautionary principle. Sci Total Environ. 288(1):155–165.

Drayson K, Wood G, Thompson S. 2015. Assessing the quality of the ecological component of English Environmental Statements. J Environ Manage. 160:241–253.

Duarte CM, Krause-Jensen D. 2020. The restoration imperative to achieve a sustainable ocean economy nobody foretold in 1871. One Earth. 3(6):669–671.

Dunlap RE, Van Liere KD. 1978. The "new environmental paradigm." J Environ Educ. 9(4):10–19.

Dunlap RE, Van Liere KD, Mertig AG, Jones RE. 2000. New trends in measuring environmental attitudes: measuring endorsement of the new ecological paradigm: a revised NEP scale. J Soc Issues. 56(3):425–442.

Durden JM, Lallier LE, Murphy K, Jaeckel A, Gjerde K, Jones DOB. 2018. Environmental Impact Assessment process for deep-sea mining in 'the Area.' Mar Policy. 87:194–202.

Durden JM, Murphy K, Jaeckel A, Van Dover CL, Christiansen S, Gjerde K, Ortega A, Jones DOB. 2017. A procedural framework for robust environmental management of deep-sea mining projects using a conceptual model. Mar Policy. 84(Supplement C):193–201.

Eikeset AM, Mazzarella AB, Davíðsdóttir B, Klinger DH, Levin SA, Rovenskaya E, Stenseth NC. 2018. What is blue growth? The semantics of "Sustainable Development" of marine environments. Mar Policy. 87:177–179.

Elshkaki A, Graedel TE, Ciacci L, Reck BK. 2016. Copper demand, supply, and associated energy use to 2050. Glob Environ Change. 39:305–315.

Enqvist JP, West S, Masterson VA, Haider LJ, Svedin U, Tengö M. 2018. Stewardship as a boundary object for sustainability research: linking care, knowledge and agency. Landsc Urban Plan. 179:17–37.

Fenton N, Neil M. 2012. Risk assessment and decision analysis with Bayesian networks. Crc Press.

Fleming LE, Maycock B, White MP, Depledge MH. 2019. Fostering human health through ocean sustainability in the 21st century. People Nat. 1(3):276–283.

Folkersen MV, Fleming CM, Hasan S. 2019. Depths of uncertainty for deep-sea policy and legislation. Glob Environ Change. 54:1–5. doi:10.1016/j.gloenvcha.2018.11.002.

Friedman J, Hastie T, Tibshirani R. 2000. Additive logistic regression: a statistical view of boosting (with discussion and a rejoinder by the authors). Ann Stat. 28(2):337–407.

Gee K. 2019. The ocean perspective. In: Maritime Spatial Planning. Palgrave Macmillan, Cham. p. 23–45.

Gelcich S, Buckley P, Pinnegar JK, Chilvers J, Lorenzoni I, Terry G, Guerrero M, Castilla JC, Valdebenito A, Duarte CM. 2014. Public awareness, concerns, and priorities about anthropogenic impacts on marine environments. Proc Natl Acad Sci. 111(42):15042–15047.

Ginzky H, Singh PA, Markus T. 2020. Strengthening the International Seabed Authority's knowledge-base: addressing uncertainties to enhance decision-making. Mar Policy. 114:103823.

Glasby GP, Emelyanov EM, Zhamoida VA, Baturin GN, Leipe T, Bahlo R, Bonacker P. 1997. Environments of formation of ferromanganese concretions in the Baltic Sea: a critical review. Geol Soc Lond Spec Publ. 119(1):213–237.

Glasson J, Therivel R, Chadwick A. 2013. Introduction to environmental impact assessment. Routledge.

Gollner S, Kaiser S, Menzel L, Jones DOB, Brown A, Mestre NC, van Oevelen D, Menot L, Colaço A, Canals M, et al. 2017. Resilience of benthic deep-sea fauna to mining activities. Mar Environ Res. 129:76–101.

González FJ, Somoza L, Lunar R, Martínez-Frías J, Rubí JAM, Torres T, Ortiz JE, Díaz-del-Río V. 2010. Internal features, mineralogy and geochemistry of ferromanganese nodules from the Gulf of Cadiz: The role of the Mediterranean Outflow Water undercurrent. J Mar Syst. 80(3):203–218.

González-Hidalgo M, Zografos C. 2020. Emotions, power, and environmental conflict: Expanding the 'emotional turn' in political ecology. Prog Hum Geogr. 44(2):235–255.

Gregory R, Failing L, Ohlson D, McDaniels TL. 2006. Some pitfalls of an overemphasis on science in environmental risk management decisions. J Risk Res. 9(7):717–735.

Guerra F, Grilo C, Pedroso NM, Cabral H. 2015. Environmental Impact Assessment in the marine environment: A comparison of legal frameworks. Environ Impact Assess Rev. 55:182–194.

Gustafsod PE. 1998. Gender Differences in risk perception: Theoretical and methodological erspectives. Risk Anal. 18(6):805–811.

Hackett J, Harrington S. 2018. Beasts of the deep: sea creatures and popular culture. Indiana University Press.

Halpern BS, Frazier M, Afflerbach J, Lowndes JS, Micheli F, O'Hara C, Scarborough C, Selkoe KA. 2019. Recent pace of change in human impact on the world's ocean. Sci Rep. 9(1):1–8.

Halpern BS, Frazier M, Potapenko J, Casey KS, Koenig K, Longo C, Lowndes JS, Rockwood RC, Selig ER, Selkoe KA. 2015. Spatial and temporal changes in cumulative human impacts on the world's ocean. Nat Commun. 6(1):1–7.

Halpern BS, Longo C, Hardy D, McLeod KL, Samhouri JF, Katona SK, Kleisner K, Lester SE, O'Leary J, Ranelletti M, et al. 2012. An index to assess the health and benefits of the global ocean. Nature. 488(7413):615–620.

Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'agrosa C, Bruno JF, Casey KS, Ebert C, Fox HE, et al. 2008. A global map of human impact on marine ecosystems. Science. 319(5865):948–952.

Hannigan J. 2016. The geopolitics of deep oceans. John Wiley & Sons.

Hannington M, Petersen S, Krätschell A. 2017. Subsea mining moves closer to shore. Nat Geosci.

Hansen AM, Vanclay F, Croal P, Skjervedal A-SH. 2016. Managing the social impacts of the rapidly-expanding extractive industries in Greenland. Extr Ind Soc. 3(1):25–33.

Hansson SO. 2009. From the casino to the jungle. Synthese. 168(3):423–432.

Harden-Davies H. 2017. Deep-sea genetic resources: new frontiers for science and stewardship in areas beyond national jurisdiction. Deep Sea Res Part II Top Stud Oceanogr. 137:504–513.

Hart BT, Pollino CA. 2008. Increased Use of Bayesian Network Models Will Improve Ecological Risk Assessments. Hum Ecol RISK Assess. 14(5):851–853.

Hassall KL, Dailey G, Zawadzka J, Milne AE, Harris JA, Corstanje R, Whitmore AP. 2019. Facilitating the elicitation of beliefs for use in Bayesian Belief modelling. Environ Model Softw. 122:104539.

Haugan PM, Levin LA, Amon D, Hemer M, Lily H, Nielsen FG. 2020. What Role for Ocean-Based Renewable Energy and Deep Seabed Minerals in a Sustainable Future. World Resour Inst.

Hein JR, Mizell K, Koschinsky A, Conrad TA. 2013. Deep-ocean mineral deposits as a source of critical metals for high-and green-technology applications: Comparison with land-based resources. Ore Geol Rev. 51:1–14.

HELCOM H. 2013. Technical Report on the HELCOM Underwater Biotope and habitat classification. In: Balt. Sea Environ. Proc. Vol. 139.

Hiddink JG, Jennings S, Sciberras M, Bolam SG, Cambiè G, McConnaughey RA, Mazor T, Hilborn R, Collie JS, Pitcher CR. 2019. Assessing bottom trawling impacts based on the longevity of benthic invertebrates. J Appl Ecol. 56(5):1075–1084.

Hodgson EE, Essington TE, Samhouri JF, Allison EH, Bennett NJ, Bostrom A, Cullen AC, Kasperski S, Levin PS, Poe MR. 2019. Integrated Risk Assessment for the Blue Economy. Front Mar Sci. 6. 609.

Hodgson EE, Halpern BS, Essington TE. 2019. Moving Beyond Silos in Cumulative Effects Assessment. Front Ecol Evol. 7, 211.

Holsman K, Samhouri J, Cook G, Hazen E, Olsen E, Dillard M, Kasperski S, Gaichas S, Kelble CR, Fogarty M. 2017. An ecosystem-based approach to marine risk assessment. Ecosyst Health Sustain. 3(1):e01256.

Hyman J, Stewart RA, Sahin O. 2021. Adaptive management of deep-seabed mining projects: a systems approach. Integr Environ Assess Manag.

Ingri J. 1985. Geochemistry of ferromanganese concretions and associated sediments in the Gulf of Bothnia. DIVA. [accessed 2018 Sep 21]. http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-17413.

ISA. 2018. Draft regulations on exploitation of mineral resources in the Area. https://isa.org.jm/files/files/documents/25C-18-en_0.pdf.

Jaeckel A. 2016. Deep seabed mining and adaptive management: the procedural challenges for the International Seabed Authority. Mar Policy. 70:205–211.

Jamieson AJ, Singleman G, Linley TD, Casey S. 2020. Fear and loathing of the deep ocean: why don't people care about the deep sea? ICES J Mar Sci.78(3)

Jardine C, Hrudey S, Shortreed J, Craig L, Krewski D, Furgal C, McColl S. 2003. Risk management frameworks for human health and environmental risks. J Toxicol Environ Health B Crit Rev. 6(6):569–718.

Jax K, Calestani M, Chan KM, Eser U, Keune H, Muraca B, O'Brien L, Potthast T, Voget-Kleschin L, Wittmer H. 2018. Caring for nature matters: a relational approach for understanding nature's contributions to human well-being. Curr Opin Environ Sustain. 35:22–29.

Jefferson R, McKinley E, Capstick S, Fletcher S, Griffin H, Milanese M. 2015. Understanding audiences: making public perceptions research matter to marine conservation. Ocean Coast Manag. 115:61–70.

JOGMEC. 2018. Japan Oil, Gas and Metals National Corp. 2018, JOGMEC annual report March 2018: Tokyo, Japan (Accessed April 23, 2020, at http://www.jogmec.go.jp/content/300350621.pdf).

Jones DOB, Kaiser S, Sweetman AK, Smith CR, Menot L, Vink A, Trueblood D, Greinert J, Billett DSM, Arbizu PM, et al. 2017. Biological responses to disturbance from simulated deep-sea polymetallic nodule mining. Vopel KC, editor. PLOS ONE. 12(2):e0171750.

Jones NA, Ross H, Shaw S, Witt K, Pinner B, Rissik D. 2016. Values towards waterways in south east Queensland: Why people care. Mar Policy. 71:121–131. doi:10.1016/j.marpol.2016.05.027.

Jouffray J-B, Blasiak R, Norström AV, Österblom H, Nyström M. 2020. The Blue Acceleration: The Trajectory of Human Expansion into the Ocean. One Earth. 2(1):43–54.

Kagan S. 1998. Rethinking Intrinsic Value. J Ethics. 2(4):277–297.

Kaikkonen L, Parviainen T, Rahikainen M, Uusitalo L, Lehikoinen A. 2021. Bayesian Networks in Environmental Risk Assessment: A Review. Integr Environ Assess Manag. 17(1):62–78.

Kaskela AM, Rousi H, Ronkainen M, Orlova M, Babin A, Gogoberidze G, Kostamo K, Kotilainen AT, Neevin I, Ryabchuk D, et al. 2017. Linkages between benthic assemblages and physical environmental factors: The role of geodiversity in Eastern Gulf of Finland ecosystems. Cont Shelf Res. 142:1-13.

Kasperson RE, Renn O, Slovic P, Brown HS, Emel J, Goble R, Kasperson JX, Ratick S. 1988. The social amplification of risk: A conceptual framework. Risk Anal. 8(2):177–187.

Kearns R, Collins D. 2012. Feeling for the coast: the place of emotion in resistance to residential development. Soc Cult Geogr. 13(8):937–955.

Kellert SR. 1993. Values and perceptions of invertebrates. Conserv Biol. 7(4):845–855.

Kellert SR. 1997. The value of life: Biological diversity and human society. Island Press.

Khripounoff A, Caprais J-C, Crassous P, Etoubleau J. 2006. Geochemical and biological recovery of the disturbed seafloor in polymetallic nodule fields of the Clipperton-Clarion Fracture Zone (CCFZ) at 5,000-m depth. Limnol Oceanogr. 51(5):2033–2041.

Klain SC, Olmsted P, Chan KMA, Satterfield T. 2017. Relational values resonate broadly and differently than intrinsic or instrumental values, or the New Ecological Paradigm. PLOS ONE. 12(8):e0183962.

Kotilainen AT, Kiviluoto S, Kurvinen L, Sahla M, Ehrnsten E, Laine A, Lax HG, Kontula T, Blankett P, Ekebom J, et al. 2018. Itämeri. Julk.: Kontula, T. & Raunio, A. (toim.). Suomen luontotyyppien uhanalaisuus 2018. Luontotyyppien punainen kirja – Osa 2: Luontotyyppien kuvaukset (in

Finnish, Summary in English). Suomen ympäristökeskus & ympäristöministeriö, Helsinki. Suomen ympäristö 5/2018. s. 15–98.

Kovalenko KE, Thomaz SM, Warfe DM. 2012. Habitat complexity: approaches and future directions. Hydrobiologia. 685(1):1–17.

Kuhlman T, Farrington J. 2010. What is sustainability? Sustainability. 2(11):3436–3448.

Kuhn T, Wegorzewski A, Rühlemann C, Vink A. 2017. Composition, formation, and occurrence of polymetallic nodules. In: Deep-Sea Mining. Springer. p. 23–63.

Kung A, Svobodova K, Lèbre E, Valenta R, Kemp D, Owen JR. 2020 Nov 19. Governing deep sea mining in the face of uncertainty. J Environ Manage.:111593.

Lauritzen SL, Spiegelhalter DJ. 1988. Local computations with probabilities on graphical structures and their application to expert systems. J R Stat Soc Ser B Methodol. 50(2):157–194.

Leach M, Reyers B, Bai X, Brondizio ES, Cook C, Díaz S, Espindola G, Scobie M, Stafford-Smith M, Subramanian SM. 2018. Equity and sustainability in the Anthropocene: a social–ecological systems perspective on their intertwined futures. Glob Sustain. 1.

Lee K-H, Noh J, Khim JS. 2020. The Blue Economy and the United Nations' sustainable development goals: Challenges and opportunities. Environ Int. 137:105528.

Leinikki E. 2020. The Ecological Role of Iron-Manganese Concretions.

Leiserowitz A. 2006. Climate change risk perception and policy preferences: The role of affect, imagery, and values. Clim Change. 77(1–2):45–72.

Levin LA, Amon DJ, Lily H. 2020. Challenges to the sustainability of deep-seabed mining. Nat Sustain. 3(10):784–794.

Levin PS, Fogarty MJ, Murawski SA, Fluharty D. 2009. Integrated ecosystem assessments: developing the scientific basis for ecosystem-based management of the ocean. PLoS Biol. 7(1):e1000014.

Loewenstein GF, Weber EU, Hsee CK, Welch N. 2001. Risk as feelings. Psychol Bull. 127(2):267.

Long RD, Charles A, Stephenson RL. 2015. Key principles of marine ecosystem-based management. Mar Policy. 57:53–60.

Lotze HK, Coll M, Magera AM, Ward-Paige C, Airoldi L. 2011. Recovery of marine animal populations and ecosystems. Trends Ecol Evol. 26(11):595–605.

Lotze HK, Guest H, O'Leary J, Tuda A, Wallace D. 2018. Public perceptions of marine threats and protection from around the world. Ocean Coast Manag. 152:14–22.

Lubchenco J, Gaines SD. 2019. A new narrative for the ocean. Science 364. (6444): 911-911.

Lumber R, Richardson M, Sheffield D. 2017. Beyond knowing nature: Contact, emotion, compassion, meaning, and beauty are pathways to nature connection. PLOS ONE. 12(5):e0177186.

Mason C, Paxton G, Parr J, Boughen N. 2010. Charting the territory: Exploring stakeholder reactions to the prospect of seafloor exploration and mining in Australia. Mar Policy. 34(6):1374–1380.

Mathevet R, Bousquet F, Raymond CM. 2018. The concept of stewardship in sustainability science and conservation biology. Biol Conserv. 217:363–370.

Mero JL. 1965. The mineral resources of the sea. Elsevier.

Miljutin DM, Miljutina MA, Arbizu PM, Galéron J. 2011. Deep-sea nematode assemblage has not recovered 26 years after experimental mining of polymetallic nodules (Clarion-Clipperton Fracture Zone, Tropical Eastern Pacific). Deep Sea Res Part Oceanogr Res Pap. 58(8):885–897.

Miller KA, Thompson KF, Johnston P, Santillo D. 2018. An Overview of Seabed Mining Including the Current State of Development, Environmental Impacts, and Knowledge Gaps. Front Mar Sci. 4. doi:10.3389/fmars.2017.00418. [accessed 2018 Jan 11]. https://www.frontiersin.org/articles/10.3389/fmars.2017.00418/full.

Morales O, Kurowicka D, Roelen A. 2008. Eliciting conditional and unconditional rank correlations from conditional probabilities. Reliab Eng Syst Saf. 93(5):699–710.

Munn E. 1979. Environmental impact assessment.

Nansai K, Nakajima K, Kagawa S, Kondo Y, Suh S, Shigetomi Y, Oshita Y. 2014. Global flows of critical metals necessary for low-carbon technologies: the case of neodymium, cobalt, and platinum. Environ Sci Technol. 48(3):1391–1400.

Nash KL, Cvitanovic C, Fulton EA, Halpern BS, Milner-Gulland EJ, Watson RA, Blanchard JL. 2017. Planetary boundaries for a blue planet. Nat Ecol Evol. 1(11):1625–1634.

Neimanis A, Åsberg C, Hayes S. 2015. Post-humanist imaginaries. In: Research Handbook on Climate Governance. Edward Elgar Publishing.

Newell RC, Seiderer LJ, Hitchcock DR. 1998. The impact of dredging works in coastal waters: a review of the sensitivity to disturbance and subsequent recovery of biological resources on the sea bed. Oceanogr Mar Biol Annu Rev. 36:127–178.

Newell RC, Seiderer LJ, Simpson NM, Robinson JE. 2004. Impacts of marine aggregate dredging on benthic macrofauna off the south coast of the United Kingdom. J Coast Res.:115–125.

Nielsen TD, Jensen FV. 2009. Bayesian networks and decision graphs. Springer Science & Business Media.

Novaglio C, Bax N, Boschetti F, Emad GR, Frusher S, Fullbrook L, Hemer M, Jennings S, Van Putten I, Robinson L. 2021. Deep aspirations: towards a sustainable offshore blue economy. Rev. Fish Biol 1-22.

O'neill J, Holland A, Light A. 2008. Environmental values. Routledge.

Orcutt BN, Bradley JA, Brazelton WJ, Estes ER, Goordial JM, Huber JA, Jones RM, Mahmoudi N, Marlow JJ, Murdock S. 2018. Impacts of deep-sea mining on microbial ecosystem services. Limnol Oceanogr.65(7).

Parviainen T, Lehikoinen A, Kuikka S, Haapasaari P. 2019. Risk frames and multiple ways of knowing: Coping with ambiguity in oil spill risk governance in the Norwegian Barents Sea. Environ Sci Policy. 98:95–111.

Pascual U, Balvanera P, Díaz S, Pataki G, Roth E, Stenseke M, Watson RT, Dessane EB, Islar M, Kelemen E. 2017. Valuing nature's contributions to people: the IPBES approach. Curr Opin Environ Sustain. 26:7–16.

Pearl J. 1986. Fusion, propagation, and structuring in belief networks. Artif Intell. 29(3):241–288.

Pearl J. 1988. Embracing causality in default reasoning. Artif Intell. 35(2):259–271.

Pearl J. 2009. Causality. Cambridge university press.

Peduzzi P. 2014. Sand, rarer than one thinks. Environ Dev. 11:208–218.

Peel J. 2005. The precautionary principle in practice: environmental decision-making and scientific uncertainty. Federation Press.

Perdicoúlis A, Glasson J. 2006. Causal networks in EIA. Environ Impact Assess Rev. 26(6):553–569.

Perdicoúlis A, Glasson J. 2012. How clearly is causality communicated in eia? J Environ Assess Policy Manag. 14(03):1250020.

Pérez EJM. 2017. The Environmental Legal Framework for the Development of Blue Energy in Europe. In: The Future of the Law of the Sea. Springer, Cham. p. 127–144.

Perkins HE. 2010. Measuring love and care for nature. J Environ Psychol. 30(4):455–463.

Petersen S, Kraeschell A, Augustin N, Jamieson J, Hein JR, Hannington MD. 2016. News from the seabed - Geological characteristics and resource potential of deep-sea mineral resources. Mar Policy. 70:175–187.

Peukert A, Petersen S, Greinert J, Charlot F. 2018. Seabed Mining. In: Submarine Geomorphology. Springer. p. 481–502.

Pollino CA, Woodberry O, Nicholson A, Korb K, Hart BT. 2007. Parameterisation and evaluation of a Bayesian network for use in an ecological risk assessment. Environ Model Softw. 22(8):1140–1152.

Quemmerais-Amice F, Barrere J, La Rivière M, Contin G, Bailly D. 2020. A Methodology and Tool for Mapping the Risk of Cumulative Effects on Benthic Habitats. Front Mar Sci. 7. 966.

Ramirez-Llodra E, Tyler PA, Baker MC, Bergstad OA, Clark MR, Escobar E, Levin LA, Menot L, Rowden AA, Smith CR, et al. 2011. Man and the Last Great Wilderness: Human Impact on the Deep Sea. PLOS ONE. 6(8):e22588.

Reid S. 2020. Solwara 1 and the Sessile Ones. Blue Leg Life Laws Seas.:25–44.

Renn O. 1998. The role of risk perception for risk management. Reliab Eng Syst Saf. 59(1):49–62.

Reunamo A, Yli-Hemminki P, Nuutinen J, Lehtoranta J, Jørgensen KS. 2017. Degradation of Crude Oil and PAHs in Iron–Manganese Concretions and Sediment from the Northern Baltic Sea. Geomicrobiol J. 34(5):385–399.

Sagebiel J, Schwartz C, Rhozyel M, Rajmis S, Hirschfeld J. 2016. Economic valuation of Baltic marine ecosystem services: blind spots and limited consistency. ICES J Mar Sci. 73(4):991–1003.

Sahlin U, Helle I, Perepolkin D. 2021. "This Is What We Don't Know": Treating Epistemic Uncertainty in Bayesian Networks for Risk Assessment. Integr Environ Assess Manag. 17(1):221–232.

Schindler DE, Hilborn R. 2015. Prediction, precaution, and policy under global change. Science. 347(6225):953–954.

Schwartz SH. 1992. Universals in the content and structure of values: Theoretical advances and empirical tests in 20 countries. Adv Exp Soc Psychol. 25(1):1–65.

Schwartz SH. 1994. Are there universal aspects in the structure and contents of human values? J Soc Issues. 50(4):19–45.

Scutari M. 2009. Learning Bayesian networks with the bnlearn R package. ArXiv Prepr ArXiv09083817.

Scutari M, Denis J-B. 2014. Bayesian networks: with examples in R. CRC press.

Simon-Lledó E, Bett BJ, Huvenne VAI, Köser K, Schoening T, Greinert J, Jones DOB. 2019. Biological effects 26 years after simulated deep-sea mining. Sci Rep. 9(1):8040.

Sjöberg L. 2000. Factors in risk perception. Risk Anal. 20(1):1–12.

Slovic P, Finucane ML, Peters E, MacGregor DG. 2004. Risk as analysis and risk as feelings: Some thoughts about affect, reason, risk, and rationality. Risk Anal Int J. 24(2):311–322.

Slovic S, Slovic P. 2013. Numbers and nerves: Toward an affective apprehension of environmental risk. In: The Feeling of Risk. Routledge. p. 107–112.

Smith CR, Tunnicliffe V, Colaço A, Drazen JC, Gollner S, Levin LA, Mestre NC, Metaxas A, Molodtsova TN, Morato T. 2020. Deep-sea misconceptions cause underestimation of seabed-mining impacts. Trends Ecol Evol. 35(10):853–857.

Sobkow A, Traczyk J, Zaleskiewicz T. 2016. The affective bases of risk perception: negative feelings and stress mediate the relationship between mental imagery and risk perception. Front Psychol. 7:932.

Sonter LJ, Dade MC, Watson JE, Valenta RK. 2020. Renewable energy production will exacerbate mining threats to biodiversity. Nat Commun. 11(1):1–6.

Starr C. 1969. Social benefit versus technological risk. Science.:1232–1238.

Stelzenmueller V, Fock HO, Gimpel A, Rambo H, Diekmann R, Probst WN, Callies U, Bockelmann F, Neumann H, Kroencke I. 2015. Quantitative environmental risk assessments in the context of marine spatial management: current approaches and some perspectives. ICES J Mar Sci. 72(3):1022–1042.

Stephenson RL, Hobday AJ, Allison EH, Armitage D, Brooks K, Bundy A, Cvitanovic C, Dickey-Collas M, Grilli N de M, Gomez C, et al. 2021. The Quilt of Sustainable Ocean Governance: Patterns for Practitioners. Front Mar Sci. 8 120

Stern PC, Dietz T. 1994. The Value Basis of Environmental Concern. J Soc Issues. 50(3):65–84.

Sultana F. 2015. Emotional political ecology. In: The international handbook of political ecology. Edward Elgar Publishing.

Šunde C. 2008. The open horizon: exploring spiritual and cultural values of the oceans and coasts. Edward Elgar: Cheltenham, UK.

Suter II GW. 2016. Ecological risk assessment. CRC press.

Tadaki M, Sinner J, Chan K. 2017. Making sense of environmental values: a typology of concepts. Ecol Soc. 22(1).

Thiel H, Schriever G, Ahnert A, Bluhm H, Borowski C, Vopel K. 2001. The large-scale environmental impact experiment DISCOL—reflection and foresight. Deep Sea Res Part II Top Stud Oceanogr. 48(17):3869–3882.

Torres PC, Morsello C, Parry L, Pardini R. 2016. Who cares about forests and why? Individual values attributed to forests in a post-frontier region in Amazonia. PloS One. 11(12):e0167691.

Tversky A, Kahneman D. 1979. Prospect theory: An analysis of decision under risk. Econometrica. 47(2):263–291.

UNESCO. 2019. United Nations Decade of Ocean Science for Sustainable Development (2021–2030) (UNESCO, 2019); https://www.oceandecade.org/.

Van Nijen K, Van Passel S, Squires D. 2018. A stochastic techno-economic assessment of seabed mining of polymetallic nodules in the Clarion Clipperton Fracture Zone. Mar Policy. 95:133–141.

Vanreusel A, Hilario A, Ribeiro PA, Menot L, Arbizu PM. 2016. Threatened by mining, polymetallic nodules are required to preserve abyssal epifauna. Sci Rep. 6:srep26808.

Varis O, Kettunen J, Sirviö H. 1990. Bayesian influence diagram approach to complex environmental management including observational design. Comput Stat Data Anal. 9(1):77–91.

Veillette J, Juniper SK, Gooday AJ, Sarrazin J. 2007. Influence of surface texture and microhabitat heterogeneity in structuring nodule faunal communities. Deep Sea Res Part Oceanogr Res Pap. 54(11):1936–1943.

Vereshchagin OS, Perova EN, Brusnitsyn AI, Ershova VB, Khudoley AK, Shilovskikh VV, Molchanova EV. 2019. Ferro-manganese nodules from the Kara Sea: Mineralogy, geochemistry and genesis. Ore Geol Rev. 106:192–204.

Vidal O, Rostom F, François C, Giraud G. 2017. Global Trends in Metal Consumption and Supply: The Raw Material–Energy Nexus. Elements. 13(5):319–324.

Virtanen E. 2020. Decision support for seascape conservation and ecosystem-based marine management in the northern Baltic Sea.

Virtanen EA, Norkko A, Nyström Sandman A, Viitasalo M. 2019. Identifying areas prone to coastal hypoxia–the role of topography. Biogeosciences. 16(16).

Virtanen EA, Viitasalo M, Lappalainen J, Moilanen A. 2018. Evaluation, gap analysis, and potential expansion of the Finnish marine protected area network. Front Mar Sci. 5:402.

Vonnahme TR, Molari M, Janssen F, Wenzhöfer F, Haeckel M, Titschack J, Boetius A. 2020. Effects of a deep-sea mining experiment on seafloor microbial communities and functions after 26 years. Sci Adv. 6(18):eaaz5922.

Voyer M, van Leeuwen J. 2019. 'Social license to operate 'in the Blue Economy. Resour Policy. 62:102–113.

Voyer M, Quirk G, McIlgorm A, Azmi K. 2018. Shades of blue: what do competing interpretations of the Blue Economy mean for oceans governance? J Environ Policy Plan. 20(5):595–616.

Wachinger G, Renn O, Begg C, Kuhlicke C. 2013. The risk perception paradox—implications for governance and communication of natural hazards. Risk Anal. 33(6):1049–1065.

Wang R. 2011. The precautionary principle in maritime affairs. WMU J Marit Aff. 10(2):143.

Washburn TW, Turner PJ, Durden JM, Jones DOB, Weaver P, Van Dover CL. 2019. Ecological risk assessment for deep-sea mining. Ocean Coast Manag. 176:24–39.

Werner C, Bedford T, Cooke RM, Hanea AM, Morales-Nápoles O. 2017. Expert judgement for dependence in probabilistic modelling: A systematic literature review and future research directions. Eur J Oper Res. 258(3):801–819.

West S, Haider LJ, Masterson V, Enqvist JP, Svedin U, Tengö M. 2018. Stewardship, care and relational values. Curr Opin Environ Sustain. 35:30–38.

Wilson E, Stammler F. 2016. Beyond extractivism and alternative cosmologies: Arctic communities and extractive industries in uncertain times. Extr Ind Soc. 3(1):1–8.

Winterhalter B. 1966. Pohjanlahden ja Suomenlahden rauta-mangaani-saostumista: summary: Iron-manganese concretions from the Gulf of Bothnia and the Gulf of Finland. Geologinen Tutkimuslaitos.

Winther J-G, Dai M, Rist T, Hoel AH, Li Y, Trice A, Morrissey K, Juinio-Meñez MA, Fernandes L, Unger S, et al. 2020. Integrated ocean management for a sustainable ocean economy. Nat Ecol Evol. 4(11):1451–1458.

Wolsink M. 2010. Near-shore wind power—Protected seascapes, environmentalists' attitudes, and the technocratic planning perspective. Land Use Policy. 27(2):195–203.

Wright G. 2015. Marine governance in an industrialised ocean: a case study of the emerging marine renewable energy industry. Mar Policy. 52:77–84.

Yli-Hemminki P, Jørgensen KS, Lehtoranta J. 2014. Iron–manganese concretions sustaining microbial life in the Baltic Sea: the structure of the bacterial community and enrichments in metal-oxidizing conditions. Geomicrobiol J. 31(4):263–275.

Zalik A. 2015. Trading on the offshore: territorialization and the ocean grab in the international seabed. In: Beyond Free Trade. Springer. p. 173–190.

Zhamoida V, Grigoriev A, Gruzdov K, Ryabchuk D. 2007. The influence of ferromanganese concretions-forming processes in the eastern Gulf of Finland on the marine environment. Geol Surv Finl Spec Pap. 45:21–32.

Zhamoida V, Grigoriev A, Ryabchuk D, Evdokimenko A, Kotilainen AT, Vallius H, Kaskela AM. 2017. Ferromanganese concretions of the eastern Gulf of Finland–Environmental role and effects of submarine mining. J Mar Syst. 172:178–187.

Zhong Y, Chen Z, Javier Gonzalez F, Hein JR, Zheng X, Li G, Luo Y, Mo A, Tian Y, Wang S. 2017. Composition and genesis of ferromanganese deposits from the northern South China Sea. J Asian Earth Sci. 138:110–128.